Value Stream Mapping and Improved Cell Layout in an Oilfield Services Company

by

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Abstract

This research explores potential improvements in efficiency through improved cell layout and value stream mapping. Analysis of cell layout led to significant reductions in material handling and operator movement along with reduction in cell area thereby improving overall productivity. Value stream mapping of protector assembly, one of the company's products, identified hidden inefficiencies in the value stream. A future state map using lean principles was also prepared. The major improvement areas concerned process improvement and lead time & Work-In-Process (WIP) reductions. This research also provides a detailed framework to deal with inventory inaccuracy existing in the system. Three inventory inaccuracy compensation methods were introduced and their performance was evaluated and compared using a simulation study.

Thesis Supervisor: Kamal Youcef-Toumi
Title: Professor of Mechanical Engineering

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Chapter 1: Introduction

The following are the key topics of this chapter:

- A brief overview of company background.
- A brief overview of the project.
- A brief overview of operations background.

1.1 Company Background

Schlumberger is the world's leading oilfield services company supplying technology, information solutions, and integrated project management to optimize reservoir performance for customers in the oil and gas industry. The company employs more than 66,000 people of over 140 nationalities working in more than 80 countries. Schlumberger supplies a wide range of products and services from seismic acquisition and processing; formation evaluation; well testing and directional drilling to well cementing and stimulation; artificial lift and well completions; and consulting, software, and information management [1]. The company follows a make-to-order operation model to deal with high level of product mix and demand variability.

The Artificial Lift Singapore Product Center (SPE) located in Jurong, Singapore is Schlumberger's largest Research, Development & Manufacturing plant for electric submersible pumps (ESP), down-hole pressure/temperature gauges and gas lift mandrels (GLM). The full suite of SPE products comprises of protector, motor, pump, gas separator and intake in various customizable versions [1].

1.2 Project Overview

Schlumberger, Singapore started its quest for becoming Lean[1] long back. As such it always has worked toward continuous improvement [2]as per the Lean philosophy. Under the companywide campaign for getting Lean, company decided to expand its existing manufacturing capacity. The expansion required for a major re-structuring of the company wide operations and thus gave way to streamlining the manufacturing processes at various stages of production. To continue this, several improvement projects were identified companywide. The following projects were finally chosen to be worked on:

- Head and Base Cell Re-layout.
- Lead time reductions for Protectors.
- Process Improvements for Protector Assembly.

The cell re-layout project was done with the motivation for improving productivity, reducing material handling and walking time and last but not the least reducing the cell footprint.

[1] Lean is a philosophy that aims at minimizing the resources used for production.
[2] It is a measurement driven process that continuously evaluates and improves performance.

The protector assembly process was associated with high lead times, high Work-In-Process (WIP), excessive material handling and failure to meet on time delivery schedules. Value stream map was used to identify the improvement opportunities in the protector value stream. The analysis was extended to techniques beyond value stream mapping for creating an improved manufacturing system.

1.3 Operations Background

The manufacturing facility of Schlumberger, Singapore is spread over a 550,000 square foot area and has following major subsections:

1. **Warehouse**-This stores all the incoming raw materials bought directly from the supplier. Every shop is provided with raw materials from the warehouse and the finished product of the shop is sent back for storage. These either are sold separately or act as Work-in-Process (WIP), which is later, supplied to other sections for further operations.

2. **Foundry**-This shop makes castings for the pumps, which are later stored in the supermarket situated in the same building and from there they are supplied to machining shop for further operations.

3. **Machining Shop**-This is used to machine castings from the foundry and to machine head and base parts.

4. **Sub-assembly**-This is used to do some secondary operations like pressing bush in head and base parts and machining them to right diameter.

5. **Assembly** – This shop is used for assembly of pump, motor, protector and intake as well as shaft machining and straightening cells are located in this shop. After assembly, the product is sent for welding and painting. Later it is packed and shipped to the customer.

The components are either manufactured in house or bought from outside vendors. These are then sub-assembled into basic assembly units. These sub-assembly units are then supplied to the equipment assembly area for final assembly. The major assembly units are categorized into housing & shaft, head & base, thrust bearing & bar part and rotor, each of which are taken charge of by different manufacturing sections respectively. The material flow for all the major components that go into the four products is shown in fig. 1-1.

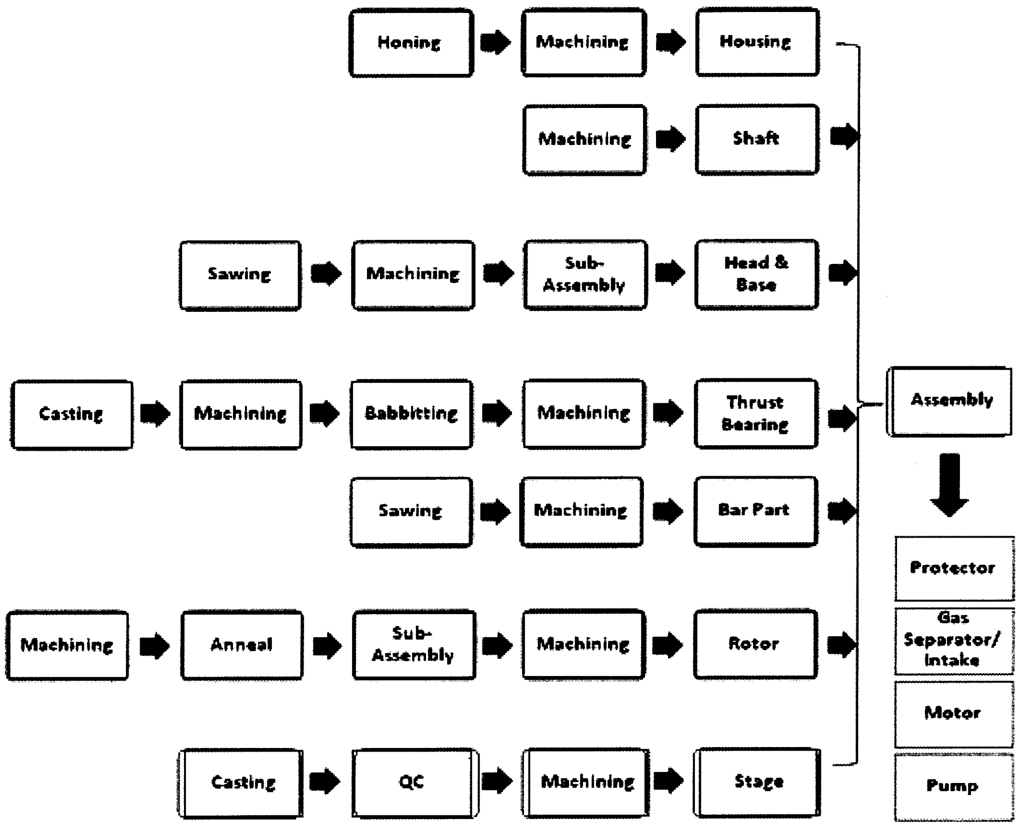

Figure 1-1: Process Map of ESP Manufacturing

However, not all components go into all the products. In general, only housing & shaft, head & base and thrust bearing & bar part which are called fixed assembly units are needed for all the products, while rotor and stage, namely optional assembly units, are used only in motor and pump respectively as shown in fig.1-2 below.

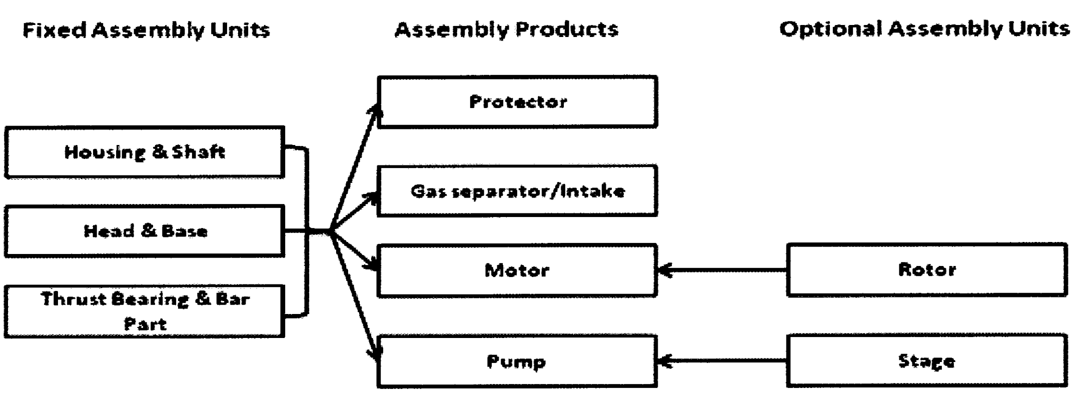

Figure 1-2: Fixed and Optional Assembly Units

1.4 Thesis Structure

This thesis is organized into 9 chapters. Chapter 1 is a description of the company, its operations and a brief project overview. Chapter 2 is a description of the problem statement in detail along with the product and processes explained. Chapter 3 is a review of the cell re-layout procedures and value stream mapping used as a tool for identifying the current state of a product assembly process and of its use in planning a future state of product assembly. Chapter 4 is a description of the methodology followed for solving the identified problems. Chapter 5 discusses the results of cell re-layout. Chapter 6 discusses Value stream mapping when applied to protector assembly to improve the assembly process. Chapter 7 extends the analysis of the assembly process of protectors beyond the techniques of value stream mapping. Chapter 8 is a summary of the results and recommendations. Chapter 9 deals with the scope for future work in this area.

Chapter 2: Problem Statement

The following are the key topics of this chapter:

- A brief discussion of head and base operations.
- Problem statement of cell re-layout in head and base machining.
- A brief discussion of protectors and associated assembly process.
- Problem statement of protector assembly.

2.1 Head and Base

2.1.1Introduction

2.1.1.1 Product Background

Head and Base are two of the essential components for motor, pump, protector and intake. The company has around 1000 different types of head and bases grouped in several product families based on the processing they undergo. The heads and bases differ based on their geometry and material.

Due to capacity constraints, some of the head and base components are outsourced to outside vendors while the remaining components are made in house.

2.1.1.2 Material flow

The entire material flow from raw material to equipment assembly is largely divided into seven stages as depicted in fig.2-2 (for parts made in house).

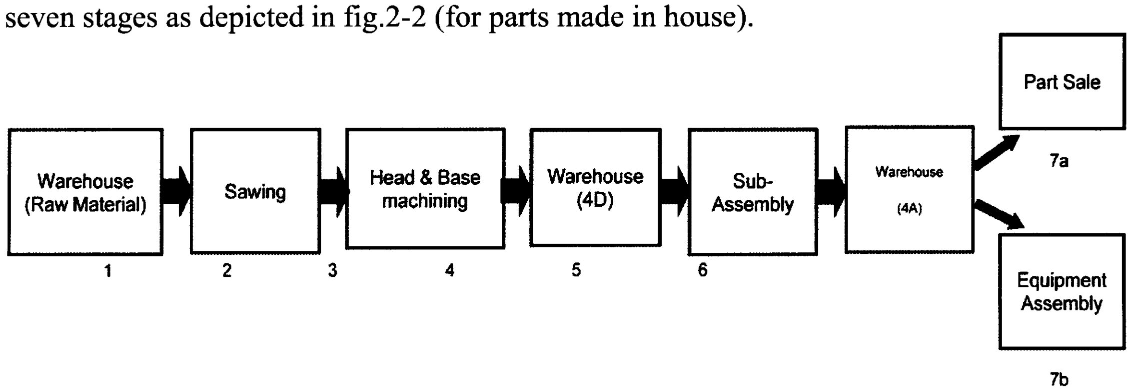

Figure 2-1: Head & base material flow (left to right)

The warehouse receives raw materials from the supplier and stores them in the warehouse. Next, warehouse issues raw material in the form of long bars to station 2 (sawing).At this station, the long bars are cut to size as per work order. This station also owns two CNC machines that perform pre-turning operations on materials when required to reduce machining time at Head & Base (station3). Sawing is done one day before the machining is due.

Next, these sawed/pre-turned parts are moved to Head and Base machining (station 3). It is comprised of 8 machining cells, some organized in U-shape and others in L-shape respectively. Every cell has some primary and secondary workstations. Primary stations are the ones that contribute to shape change of raw part while the secondary stations do some touching up operations like de-burring, inspection and antirust coating. Heads and Bases grouped in several part families (based on machining process) are machined in these cells. Not all part families can be produced in every cell. Some families are only cell specific and some can be produced in more than one cell. The lot size for different parts varies from 10 to 20 pieces but it can be sometimes as small as 1 piece. The setup time varies from 2 to 4 hours. The machined parts are called "4D" parts and sent to warehouse (station 5) for storage after inspection, where they are consolidated into big wooden boxes and stored on racks.

Next, these parts are kit-up together with other accessories and sent to H&B sub-assembly (station 6) where an operator assembles bushing and washers into these followed by some welding if necessary. The finished parts called as "4A" parts are then sent back to warehouse after inspection for storage. These parts are then kit-up together with other accessories for the final assembly and sent to pre-kit station (which later supplies to assembly cells). The sub-assembled parts for part sales are sent to service stations and sold individually.

2.1.2 Problem definition

The machining shop is divided into two broad categories-head & base machining and stage machining. As part of in house capacity expansion, the company planned to expand the stage machining existing capacity by bringing in new machines. This asked for head and base to be relocated at another location within the facility. Before relocating the head and base machining cells, company wanted to examine cell layout to improve the existing operational performance.

The head and base machining had in total 8 cells. The layout of cell 1 was analyzed because of following reasons:

- Largest area occupied.
- Highest number of machines (11 stations).
- Most bulky parts among all part types.
- Highest product variety (about 230 different part types) among all 8 cells.

The cell re-layout was done with the following objectives:

1) Increasing productivity.
2) Reduction in material handling time.
3) Reduction in operator walking time.
4) Reduction in cell occupied area.
5) Improving work efficiency.

6) Reduction in Work in Process (WIP).[3]
The project falls under Lean philosophy of continuous improvement.

2.2 Protector Assembly

2.2.1 Introduction

2.2.1.1 Product Background

The Protector is one of the major products of Schlumberger's REDA production center, Singapore. This modular protector is one of the Schlumberger's patented designs and serves several purposes when installed between motor and pump in the oil well.

Protectors provide a positive seal between internal motor oil and wellbore fluids and allow for thermal expansion and contraction of the motor fluid while eliminating a pressure differential between the motor internals and the casing annulus. The protectors incorporate two elastomeric bag type sub-assemblies to create the positive seal fluid interface, and an additional labyrinth fluid chamber to provide a reservoir of motor fluid and act as a fluid interface in the presence of a potentially corrosive wellbore environment. In addition, they also carry the thrust load of the pump.

All protectors are oil-filled, positive seal, and tandem single bag, displacement type that includes at least one additional back-up labyrinth chamber in series with the bag chambers. These are specifically designed for application as part of an electrical submersible pumping system (ESP). Protectors are capable of being installed in multiple tandem configurations without modification. These are vacuum filled at assembly to eliminate air pockets in critical mechanical seal and bearing areas.

Protectors are available in a variety of configurations and are made to customer needs. These are grouped into multiple product families based on length and diameter of shaft and housing diameters (outer diameter). The protector configurations within one product family differ based on total chambers and number of each type of chambers (labyrinth/positive seal or bag). Some common components are used to assemble multiple labyrinth and / or positive seal sections in a variety of configurations to match individual well conditions.

The Modular Protector allows choosing the proper type of protection needed for specific well conditions and eliminates the need for tandem protector configurations.

The protector assembly line consists of two cells and 3 workbenches. A typical protector consists of more than 150 parts. The major parts and sub-assemblies in the modular protector system are shown in fig.2-2.

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[3] Work in process is the semi-finished goods between two stages of production.

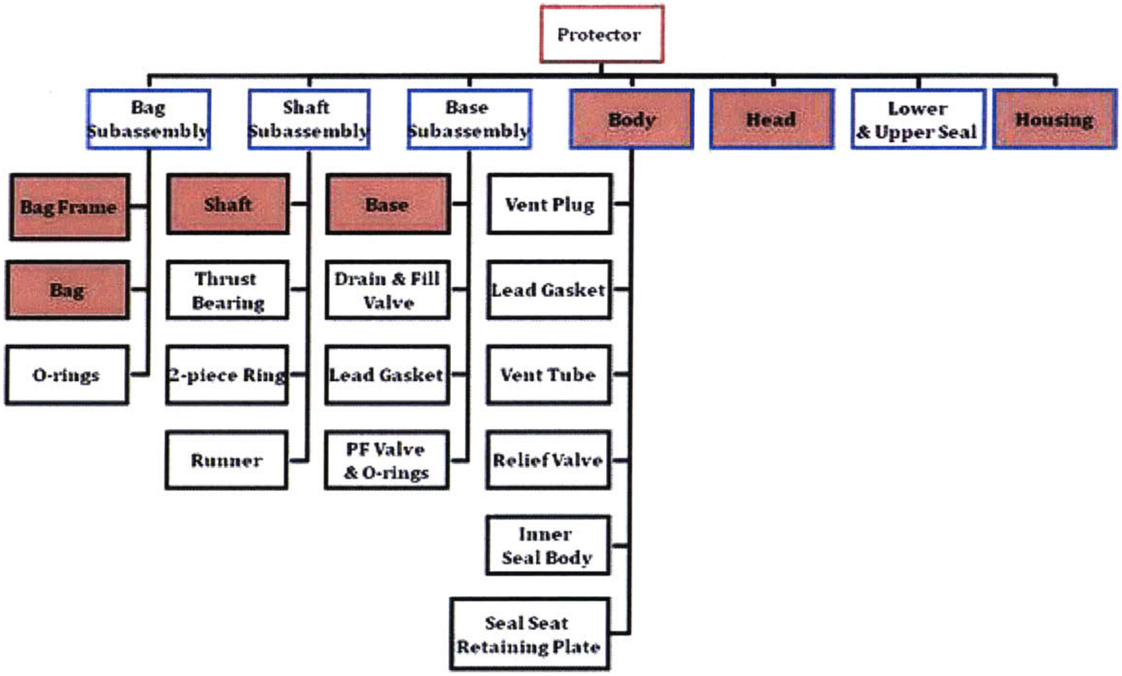

Figure 2-2: Protector Assembly Architecture (top to bottom)

2.2.1.2 Material Flow

Protectors, in general, have approximately 50 different types of parts. These are divided into two broad categories – primary parts and secondary parts. Primary parts are shown in red filled boxes in fig.2-2.The remaining parts are secondary parts. The flow of material for protectors from raw material to finished product (protector) is shown in fig.2-3.

All the primary parts except shaft are outsourced and are received at warehouse along with all the secondary parts from suppliers. These parts are stored in warehouse and only sent to assembly when scheduled by planner. Head and Base has to go to head and base sub-assembly for pressing of bush and some minor operations and are then sent back to warehouse for storage. These parts are then sent to a pre-kit station, which cleans them and organize the small parts in small wooden boxes and later supplies it to protector assembly cell. The thick dashed line shows the flow of head and base.

The shaft is made in the shaft machining area located in assembly area. The raw material for shafts, in the form of long bars, is first cut to size at sawing station. Next, these are machined and straightened to assigned tolerance. The operator at assembly cell picks the shaft from the stacks near shaft straightening station at time of assembly. After assembly protectors are filled with oil. After oil filling, they are sent for welding and painting. Later, they are packaged and shipped to customer.

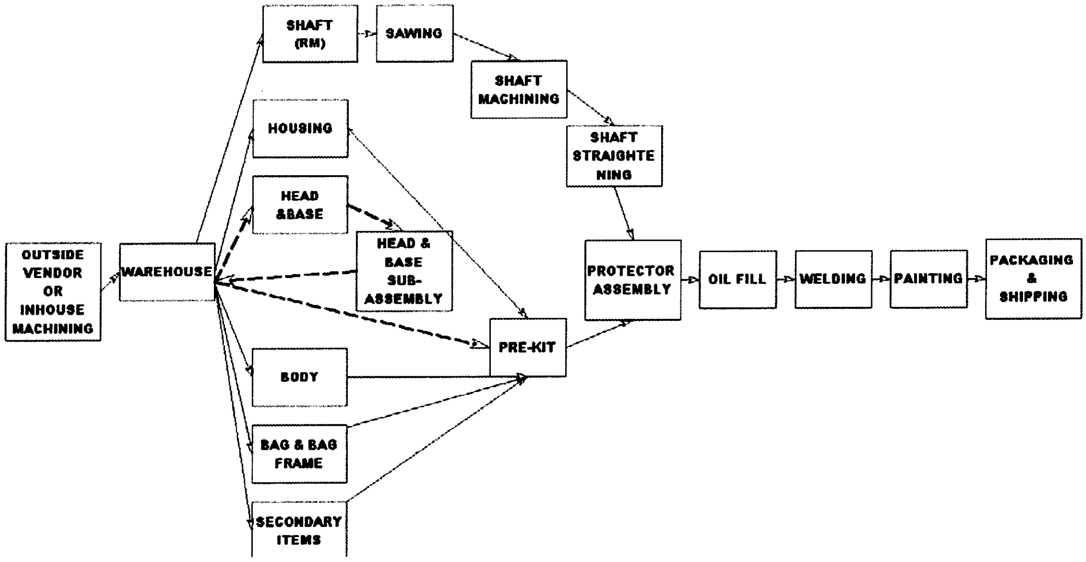

Figure 2-3: Material flow for protectors (left to right)

2.2.2 Problem Definition

As part of Lean initiative within the company, this project aimed at identification of inefficiencies in the value stream[4] of the protector and later on removing the identified inefficiencies to streamline the process and improve the operational performance. The project used Value Stream Map (VSM) as a tool for the identification of improvement opportunities. However, the analysis later was extended to techniques beyond value stream mapping for creating an improved manufacturing system.
The project specifically aimed at following:

- Lead time reductions for Protectors
- Process Improvements for Protector Assembly
- Analysis of warehouse raw material inventory

The protector assembly process was associated with high customer lead times, high Work in Process (WIP), excessive material handling and failure to meet delivery promises. In the current scenario with increasing competition, time to customer has become an important metric on which the companies are judged. Hence, every company strives for reducing their product lead times, as is the case here. Secondly, high WIP indicates process inefficiencies and considerable investment stuck up in inventory.

2.3 Summary

This chapter discusses the two main research areas explored in the thesis. The analysis of existing cell layout and the associated improvements will lead to reduction in the material

[4] Value stream for a product comprises of all the processes that go into the making of a product.

handling times and operator walking times thereby increasing productivity and work efficiency. The improvements in protector assembly will be identified using value stream mapping and will lead to reduction in lead times and improvements in protector assembly.

Chapter 3: Literature review

The following are the key topics of this chapter:

- A literature review of work in area of cell re-layout.
- An illustration of the basic methodology of cell re-layout.
- A literature review of the relevant work in the area of value stream mapping.
- An illustration of the core methodology of value stream mapping.

3.1 Cell Re-layout

A cell is a group of dissimilar machines located in close proximity and dedicated to the manufacture of a family of parts. The author Shahrukh A. Irani defines the purpose of cell redesign as follows [2]:

The objectives behind redesigning a manufacturing cell are generally reduction in lead times, work in process (WIP), queue and cycle times, and idle times.

The cell re-layout shares almost the same methodology as cell layout. The author lists down a procedure that he followed to do cell re-layout for a company X as an example to illustrate how to carry a systematic redesign of a manufacturing cell: -

1. Collection of background information
2. Updating of current layout
3. Determination of machine footprints
4. Complete inventory of objects in cell
5. Part routing, machine sequencing, and part quantities resulting in cell traffic.
6. Tracking of a sample of commonly run parts
7. Generation of alternative layouts
8. Evaluation of layouts

There is however no standard methodology in use for doing cell re-layout as such. The methodology followed by us is discussed in chapter 4.

3.2 Value stream mapping

3.2.1 Rise of value stream from Lean Manufacturing

Value stream has its roots in Lean manufacturing. Lean manufacturing is a set of principles used to enable the manufacture of goods with fewer resources.

John Krafcik, of the MIT International Motor Vehicle Program, first used the term Lean production to describe a manufacturing system that operates with minimal excess assets. Womack and Jones [3], describe Lean as the ability to do "more and more with less and less".

Today, many people associate *Lean production or Lean manufacturing, to* now more commonly known as "Toyota Production Systems (TPS)". TPS is considered by a many people to be the first manufacturing system that fully integrated the various factors of Lean manufacturing. This doesn't imply that other companies didn't embrace some or many principles that Toyota employs rather Toyota pioneered in systematically identified techniques that result in improved manufacturing performance[5] [4, 5].

The goal of TPS is to reduce costs and thereby increase profits. As part of the system, Taiichi Ohno [6], the recognized creator of TPS, identified seven types of waste. Waste is a cost that doesn't increase system throughput or the activities that are not valuable from customer point of view.

- *Overproduction:* Producing goods in excess results in accumulation of inventory and wastes worker's productive capacity creating products that are immediately not saleable.

- *Waiting: Having* workers or equipment sitting idle or unoccupied wastes the time of valuable resources.

- *Transportation:* Moving product from one site to other (within or without the plant) so that the work may be performed at the latter site is non-productive if the work could have been performed at the former site.

- *Inventory:* Having material at any stage of production, in excess of what is needed to meet customer demand increases Work in Process (or finished goods) inventory.

- *Motion:* Requiring that workers move from their ideal position(s) in which to perform their job functions causes worker times to be wasted. Moreover, it adds fatigue to the worker and thereby decreases work efficiency.

- *Over*-Processing: Using more energy or activity than is required to produce a product or adding additional value to a product that is not saleable.

- *Defects/Rework:* Creating defective goods require rework or scrapping the goods entirely.

Identifying the different types of waste, and eliminating them effectively enables a saleable product to be produced using the least amount of required resources. To add value creation [6]to a process the authors recommend following a five-step method shown in fig.3-1 and explained below.

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[5] It can be described as one which increases the production throughput with incurring any additional costs.

[6] This means to increase the leanness of the process or reducing process waste.

Value → **Value Stream** → **Flow** → **Pull** → **Perfection**

Figure3-1: Steps of Lean Thinking (Womack and Jones, 1996)

1) *Specify Value*: Determine the aspects of the product (service) that the customers deem valuable. Everything else is waste.

2) *Identify the Value Stream*: Identify the actions that are undertaken to give this product its final value.

3) *Create Flow*: Undertake actions that increase the throughput of the manufacturing system. This means creating one-piece flow and eliminating batch processing to the extent possible.

4) *Use Pull*: Use customer demand as the activator to simulate production. This means transformation from make to stock to make to order.

5) *Perfection*: This implies to continue looking /identifying wastes in the system and eliminating them until an ideal state is reached i.e. waste less system.

The TPS seven wastes and the process improvement methodology illustrated in *Lean Thinking* are complementary: the *Lean Thinking* methodology is a means to identify and act upon the seven wastes. Identifying the value stream is a step very similar in nature to identifying seven types of waste. The following steps, Create Flow, Use pull and Continuous Improvement, are methods for eliminating the various wastes. The purpose of step one is to help define a goal for the improvement effort. After the purpose for the process improvement is determined, activities that are non-value added or add waste become apparent.

Value stream mapping, discussed next, presents a visual means to undertake the identification and creation of value within a production process. This as a Lean tool is used widely among different kinds of organizations for streamlining processes either manufacturing or business. There have been numerous examples in the literature where industry is benefitted from value stream mapping.

3.2.2 Overview of Value Stream Mapping

The process of value stream mapping involves identifying the current value of a product (or family of products) and to use this current state as a basis for envisioning the future value stream. Before continuing, the value stream for a product needs to be carefully defined .The authors has defined the value stream as [7]: -

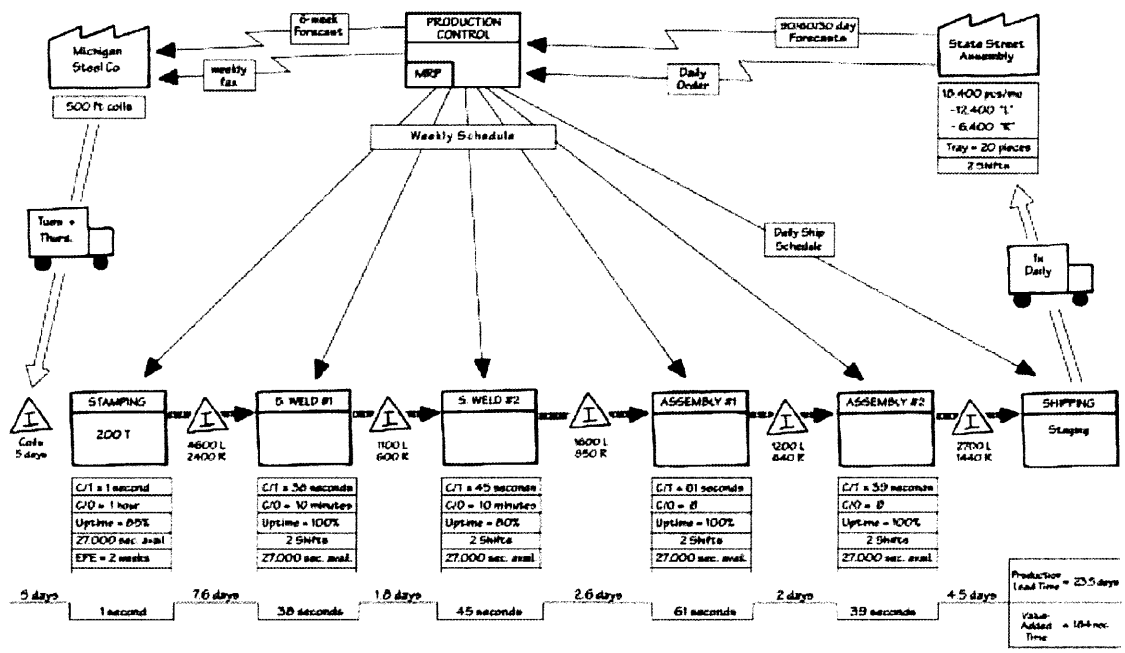
The set of all the specific actions required bringing a specific product (whether a good, a service, or increasingly a combination of two) through the three critical management tasks of any business: the problem-solving task running from concept through detailed *design and engineering to production launch, the information management task running from order–taking through detailed scheduling to delivery, and the physical transformation task preceding from raw materials to a finished production in the hands of the customers.*

The process of value stream mapping is a simple , although not necessarily easy exercise.In theory the flow of product and information from the design stage until final production needs to be tracked.Most people undertaking value stream mapping concentrate on the physical transformation and information flow tasks.One of the popular work on value stream mapping, *Learning to see* [7], value stream mapping is defined as:

Value stream mapping is the simple process of directly observing the flows of information and materials as they now occur,summarizing them visualy and then envisioning a future state with much better performance.

This thesis concentrates on only the material transformation and information flows for a major product family and its boundaries lies within the facility.

More detail on construction and implementation of value stream maps is given in section 3.2.4, Applying *Value Stream Mapping*.The value stream map starts at the raw material or component supply side of the single product (or family of products) in question.The flow of the product through the entire set of production and assembly processes it goes through.Finally,the map illustrates the flow of product to the end customer.There are two other sections of the common value stream map,the information flow section and the production summary section.The information flow section illustrates the flow of information from the planning source to the individual processes .The production summary section provides key summary characterstics.In many cases, the production summary section also contains a line summarizing the entire production time. A complete sample value stream using the illustrated methodology is shown below in the fig.3-2.



Courtesy of Learning to See [7]

Figure 3-2: Acme Value Stream Map

The above figure illustrates the value stream map of Acme Stamping used as an example to take the reader through the learning process of creating a value stream map [7]. Acme produced several components for vehicle assembly plants.

Value stream mapping doesn't stop at creating value stream maps. Once a current state map is created, it is used as a basis for creating a future state map. The authors *use* a series of eight questions to guide the value stream mapper to create a future state map. These questions are discussed in the section 3.2.4 *Applying Value Stream Mapping*. A future state map follows the entirely same method and set of icons as current state map, but depicts the suggested improvements on the map.

3.2.3 Previous Work

This section reviews the popular works in the field of value stream mapping. Value stream has been in use since late 90s as a formal technique for understanding and analyzing a value stream. The authors Womack and Jones [7], pioneered in presenting a codified approach for value stream mapping. The techniques illustrated in the book act as a step-by-step guide for analyzing an intra-organizational value stream for a product (or family of products).

The best application of value stream mapping was evaluated in the graduate thesis, *Manufacturing System Design: Flexible Manufacturing Systems and Value Stream Mapping* [8]. He conducts a survey of the usefulness of value stream mapping given different conditions. Salzman develops a value stream-mapping matrix to aid practitioners in determining the usefulness of a value stream mapping exercise. He concludes that in situations with simple value streams and management support for change, value stream mapping is most successful.

Using Value Stream Mapping to Improve Forging Process is a Master's thesis by Stephen King [9]. In his work he examined the various techniques of value stream mapping and the methods used to evaluate value stream maps to improve manufacturing systems. In his work he also used a hybrid value stream map to analyze forging of automotive ring gears.

Value Stream Analysis and Mapping for Product development is a Master's thesis by Richard L Millard [10]. He examines the applicability of value stream mapping to the area of product development. He concludes though the principles of VSM are applicable but the tools used for product and information value stream mapping needs some modification. At last, he recommends using Gantt Charts, Process Flow Diagrams, and Design Structure Matrix tools.

Some work has been done outside the conventional application area of VSM i.e. manufacturing [11]. The author took ideas from VSM in manufacturing and applied it to map different processes required to serve customers at British Telecom (BT). First a current state map was prepared using similar techniques as in manufacturing and then by applying a set of Lean principles a future state map was prepared to eliminate waste from the system.

An application of VSM to redesign and analyze a project-based engineering process can be found in [12]. Hereby, the author demonstrates the application of VSM and Lean principles to knowledge-based project work environment. He concludes that tool was applicable to the work with some modifications.

In addition to above listed case studies, many trade journals list numerous examples of successful application of VSM to variety of areas from manufacturing to product design to business processes. There is also a significant amount of unpublished work on VSM. Many of the consulting firms like Ernst & Young and McKinsey use VSM frequently and have developed their own proprietary techniques of value stream mapping.

There has been some work done related to optimizing the value stream in *The Goal* by Eli Goldratt [13]. Using a narrative approach, the author illustrates the principle of understanding the goal of a manufacturing facility to optimize it. He also illustrates a case study where a fictional plant manager rescues a troubled facility by first understanding the goal and later going on to optimize it.

This literature shows some of the relevant work done in field of value stream mapping and by no means exhaustive. The key intention here is to introduce some key terms in value stream mapping and highlight some important work done relevant to our project.

The following section examines the above mentioned common value stream techniques in greater detail.

3.2.4 Applying Value Stream Mapping

The essence of value stream lies in making problem identification easier, once a complete picture of the whole value creation process is made. Womack and Jones [7] recommend that value stream mapping be done in three phases namely, current value stream, future value stream, and determination of an implementation plan.

3.2.4.1 Current State

Value stream mapping starts from illustrating the flow of a part (or part family) from the receipt of raw materials at a facility to the finished product been shipped to customer. The product family selection step is a critical one and needs to be carried out properly.
The value stream map basically needs following two inputs: -

1. All common process steps for all members of the family are needed.
2. The information flows required for manufacturing the product.

Once all this data is gathered all this material and information flows can be pictorially shown on paper by a set of icons listed in Appendix A, fig.A-1 to A-4. A sample value stream map is also shown in fig.3-2.

Concurrent to creating this map, a set of key statistics illustrating both the individual processes and manufacturing system is collected and placed in production summary area. The following process summary data is most applicable.

1. Process description
2. Available working time
3. Numbers of operators at the process
4. Changeover time
5. Process uptime
6. Scrap percent

The metrics listed above are the most common one. Some variants can also be observed. Following are the key metrics for the whole manufacturing system:

1. *System lead-time*: The entire time right from the entry of raw material into the value stream to the finished product been shipped to the customer.

2. *Product Demand*: The customer demand of the finished product per unit time. This is normally expressed as takt time.

A sample current value stream map of Acme Stamping is attached for reference in Appendix B, fig.B-1.

3.2.4.2 Future State

Once the current state is map is prepared, the next step is to create a future state map by applying Lean principles to the current state. Learning to see gives a set of eight questions to guide map-makers through mentally improving a value stream. An answer to all these questions provides a good basis for preparing a future state map.

1. What is the process takt[7] time?
2. Whether finished goods will be stored before shipping or directly shipped to customer?
3. Where can the continuous flow or pull process be used?
4. Where should supermarket or pull systems used?
5. At what point will the pacemaker be placed in the production system?
6. How should the production mix at the pacemaker[8] be leveled?
7. What increments of work will be consistently released and taken away from the pacemaker.
8. What process improvements will be needed to attain the future state?

A sample future value stream map of Acme Stamping is attached for reference, Appendix B, fig.B-2.

It should be noted that above eight questions link to the ideas of flow and pull mentioned in the Lean principles, and shows how making a value stream is vital to determining where you can improve the process.

3.2.4.3 Implementation Plan

The final step of value stream mapping is creating an Implementation Plan to help achieve the future state from the current state. The use of a value stream plan worksheet and a review worksheet is suggested.

3.3 Summary

Cell re-layout doesn't have any standard methodology by itself but it closely follows the cell layout methodology. There is ample literature cell layout available that can be consulted .Value stream mapping is a Lean tool that has been used for manufacturing, for which it came to being, to streamlining business processes. The chapter cites several examples of previous work where application of value stream mapping has helped to streamline the process and eliminate waste. Value stream mapping is divided basically into three stages, current state depicting the present condition, the second being future

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[7] Takt time = $\frac{\text{Available Working Time}}{\text{Demand during Working Time}}$ Available working time is defined the total working time in a given period minus the amount of time for breaks, lunch etc.

[8] Pacemaker is the production process for which a schedule is released and which then pulls material from upstream processes.

state by applying some Lean principles to remove waste and inefficiencies and third the implementation plan.

Chapter 4: Methodology

The following are the key topics of this chapter:

- A review methodology of cell re-layout.
- A review of methodology of Value Stream Mapping for protector assembly.

4.1 Cell Re-Layout

Cell re-layout as already mentioned in section 2.1.2 was done with the aim of improving productivity, reducing material handling and walking time as well as also reducing the area occupied by cell.

Step 1: Collection of background information

First we became familiar with the process by looking at the cell operation, talking to operators, supervisors, concerned engineers and manager. This step helped develop a better understanding of the undergoing production and associated material flows in the cell. The gathered information related to product families made in the cell, number of different types of parts made in the cell, set-ups, run-times.

Step 2: Updating of the layout

This step aimed at noting the changes in the old cell layout drawing and updating them in the new drawing to represent the current situation. This step further involved measuring every machine, workbench, tool rack and trolley footprints and updating them in the drawing.

Step 3: Data collection &analysis

This step involved gathering the relevant data and later analyzing it to identify improvement opportunities. The data collection included the following information for all the 200 different parts made in cell 1:

1. Produced in house or outsourced
2. Demand for the part in 3 years including forecasted demand for current year.
3. Components currently made in-house but about to be outsourced.
4. Required operations and associated sequence.
5. Walking times.
6. Material handling time.
7. Transit frequency between machines.

The analysis of above data helped in establishing following:

1. Machine usage (based on the demand volume).
2. Parts undergoing similar operation sequence.

3. Different operation sequences observed and percentage of parts undergoing through each sequence (based on demand volume).

Step 4: Brainstorming and Concept generation

This step aimed at generating as many alternate layouts as possible. We came up with seven layouts of which three were selected for further evaluation. The four rejected layouts were not feasible from maintenance perspective. These alternatives designs experimented with changing machine sequences and their orientations, relocating the machines and different layout shapes.

Step 5: Establishing selection criteria

This step involved selecting the important performance evaluation measures and assigning weight to them based on their relative importance. This step brought engineers and our research team together to discuss the criteria and their respective weights based on their relative importance to cell performance. We came up with five performance measures and their respective weights.

Step 6: Establishing concept selection matrix

The five layouts selected for further evaluation were evaluated against all five performance/selection criteria and a score/rating was assigned to them on a scale of 1-5. The cumulative scores were then calculated and based on them and some additional facts brought out by data analysis in step 3, a final layout was selected.

4.2 Value stream map

The current and future state maps for protector assembly were created aimed at identifying the inefficiencies/improvement opportunities in the whole process. The techniques illustrated in [5] were used as guidelines during the whole mapping process.

Step 1: Collection of process information

This step aimed at this author becoming familiar with the process. The only way possible was to go to the shop floor, observe the process and talk to people to develop a better insight of the process. This step helped develop a deep understanding of the systems that work and also those that do not work, which was precisely the whole idea behind this exercise.

Step 2: Mapping the flow

All the relevant material flows and information flows were mapped. The next step was to collect the key metrics (some of which was process specific while others were same for the whole manufacturing system), which are, as following:

1. Process cycle times
2. Changeover times
3. Number of shifts
4. Inventory
5. Product demand

The procedure followed in order to collect the cycle times and changeover data was to go to the shop floor with a stopwatch and record data. First hand observation proved valuable in understanding the situation.

Step 3: Opportunity identification

A careful study of the value stream map presented several opportunities for improvement. The aim was to target the ones that would have highest impact on the process in terms of either of the following: -

- Safety
- Quality
- Lead times & inventory

4.3 Summary

The techniques that were systemically employed for the data collection and analysis for cell layout and value stream mapping were discussed here. The methodology discussed here helped the author to identify the process inefficiencies and suggest improvements in the existing operations.

Chapter 5: Cell Re-layout

The following are the key topics of this chapter: -

- A thorough discussion of data collection and analysis of current cell layout.
- A discussion of changes suggested in current layout.

5.1 Data Collection and Analysis

The current layout of cell 1 in Head & Base machining area is shown in fig.5-1.This cell makes about 230 different parts, which are generally bulky in nature.

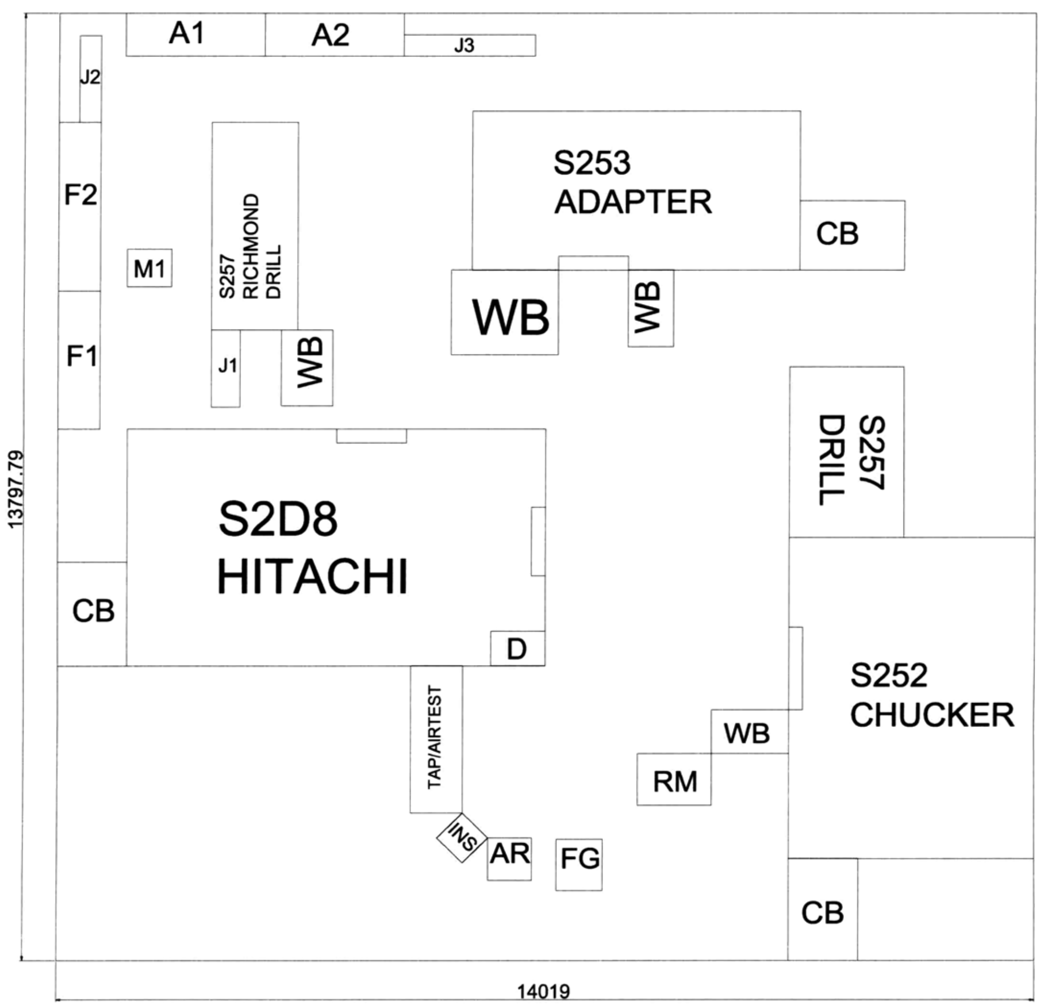

Figure 5-1: Original Cell Layout

The first step involved collecting all the background information such as, measurement of dimensions of all the mechanical elements of Cell1 that included machines, workbenches, tool racks and trolleys. These dimensions are tabulated in table 5-1. The current layout was then updated.

Table 5-1: Dimensions of Cell 1 Elements

Type	Name	Code	Length (mm)	Width (mm)	Old Sequence
Workstations (Machines):					
	CHUCKER 1	S252	6250	3500	1
	RADIAL DRILL (2 in number)	S257	2475	1640	2
	ADAPTER 1	S253	6250	3500	3
	HITACHI MILL	S2D8	7000	3400	4
	DEBURR/STENCIL		775	500	5
	TAP/DRILL		2165	750	6,7
	INSPECT		520	520	8
	ANTI-RUST		690	630	9
Miscellaneous Elements:					
	WORK TABLE		1105	650	
	WORK TABLE		1105	650	
	WORK TABLE		1540	1220	
	WORK TABLE		1105	740	
	RAW MATERIAL		1080	760	
	FG TROLLEY		760	660	
Tool Racks:					
	FIXTURE RACK	F1	2000	600	
	FIXTURE RACK	F2	2440	600	
	JAW RACK	J1	1120	415	
	JAW RACK	J2	1260	310	
	JAW RACK	J3	1890	310	
	MILL RACK	M1	640	540	
	ADAPTER RACK	A1	2000	625	
	ADAPTER RACK	A2	2000	625	

The dimensions of walkways and material handling ways (for fork lift truck) were also collected. The next step was to come up with the important selection criteria that were to be employed for the evaluation of improvements made in cell layout design. We along with the manufacturing engineers came up with the selection criteria and assigned them weights out of 100 based on their relative importance to operational performance. The weights assigned were subjective and based on engineers' experience. A large part of the non-value adding time[9] is composed of material handling and operator movement. Hence these were two most important performance measures and hence assigned highest weights. Next, was the area occupied by the cell. The last two criteria were difficult to measure and had almost equal importance. These performance criteria are listed in table 5-2.

[9] Non-Value added time – Time consumed in activities or actions taken that add no real value to the product or service.

Table 5-2: Evaluation Criteria

Rank	Evaluation Criteria	Weights	Metrics
1	Material (part) movement	37.50%	Distance (meters)
2	Walking time	31.25%	Time (minutes)
3	Total area occupied by the cell	12.50%	Area (square meters)
4	Easy set up (fixtures)	10.00%	
5	Ease of maintenance	8.75%	

Next,an analysis of sequence followed by parts was carried out.The sequence of operations(machines) differed from part to part.The table 5-3 below lists the sequence (and corresponding percentages based on volume)followed by parts.

Table 5-3: Machine sequences followed by parts

Sequence	Percentage of total parts
1,3,4	66
1,4,3	18
1,4,1	16

The above analysis revealed that the sequence followed by most parts by volume is 1(S252) – 3(S253) – 4(S2D8).So ,all the concepts generated follow the same sequence.The sequence in table 5-3 include the three major machines and is a result of analysis of high volume parts that constitute the bulk portion of cell output. A study however, was conducted on all 230 parts made in cell 1 to determine the usage frequency of machines.This study revealed that the machines S257(drill) and Tap/Air test are used by very small percentage of parts as in table 5-4.

Table 5-4: Drills and Tap/Air Test Usage

	Percentage in Total Usage		
	In-house	Outsourced	Total
S257 Drill	3.2%	2.5%	5.7%
Tap/Air Test	0.3%	18.7%	19.0%

There are two S257 drills in the cell as shown in fig.5-1 one out of those hardly being used. So, the decision to remove that machine from the cell was taken. Though Tap/Air test station is also infrequently used, but still it is being used, so it wasn't feasible to move it out of the cell. Rather it was better to get it out of the main flow and push it to side. The other possibility could be integration of the inspection (IPI) station with Tap/Air test as it had a lot of empty space. This analysis was common to all the alternative layouts.

The next step was to come up with alternate cell layouts and we generated seven alternative designs by experimenting changing machine sequences, reorienting the machines, changing layout shapes and relocating the machines. Out of these seven layouts only three were selected. The discarded layouts were not feasible from maintenance perspective else posed other practical problems. The three layouts were then made to dimensions in AutoCAD 2004.

The AutoCAD drawings helped in calculating the accumulated length of path between workstations and the total area occupied by the cell. The AutoCAD drawings of the current layout and 3 alternative concepts are attached in the Appendix C, fig.C-1 to C-4 for the reference. The material movement and walking times were evaluated by calculating the path lengths between each workstation in each layout. After collecting data concerning the material movement frequency based on routings and annual demand, annual material movement lengths within cell were calculated. The worker walking distance between workstations per unit time were then calculated, based on data collected on worker walking frequency between workstations. For the evaluation of easy set-up and easy maintenance between different layouts, there is only a minor difference and no quantitative analysis was applicable. The ratings of each layout for every selection criteria are summarized in table 5-5 & 5-6 below.

Table 5-5: Rating of Material Movement and Walking Time (mm)

	Path length between workstations (mm)					
	Current Layout	**Layout 1**	**Layout 2**	**Layout 3**	**Annual usage**	**Walking frequency Per hour**
S252-S253	8560	5374	5874	4620	6672	27
S253-S257	5423	8540	8540	8540	450	1
S253-HITACHI	5939	5939	5939	8370	5894	7
S257-HITACHI	5266	4005	4005	6240	256	1
HITACHI-DEBURR	1550	1550	1550	1690	3929	3
S253-DEBURR	6637	6637	6637	14200	1013	1
DEBURR-AIR TEST	1877	2602	2602	1410	1936	6
AIR TEST-IPI	1450	1432	1432	1960	1178	3
DEBURR-IPI	2530	650	650	650	3006	3
IPI-ANTI RUST	685	685	685	685	3743	3
ANTI RUST-FG	1645	645	645	645	3743	3
Annual material movement (km)	130.4	102.2	105.5	118.6		
Walking distance/hour(m)	325	236	250	238		
Material movement rating	1	5.0	4.5	2.7		
Machinist walking rating	1	5.0	4.4	4.9		

Table 5-6: Rating of Area Occupied

	Current	Layout 1	Layout 2	Layout 3
Length (mm)	14019	13571	13071	13832
Width (mm)	13798	11625	12028	12186
Area (m^2)	193.4	157.8	157.2	168.6
Area Rating	1	4.9	5	3.7

A concept selection matrix with all the layouts scored based on the evaluation criteria listed in table 5-2 was then constructed and is shown in table 5-7 below. The total score for a layout was calculated by summing up the multiplication of the individual scores for each performance measure with the weight assigned to it. For the scores in the first three criteria, the performance attributes are normalized to a scale of 1-5. The score of the layout with the lowest performance is defined as 1, the highest performance defined as 5 and others linearly interpolated between 1 and 5, which is shown in table 5-5, 5-6 and 5-7.

Table 5-7: Concept Selection Matrix

Performance Evaluation Measures	Weights	Current	Layout 1	Layout 2	Layout 3
Material (part) movement	38%	1.0	5.0	4.5	2.7
Walking time	31%	1	5.0	4.5	2.7
Total area occupied by the cell	13%	1	4.9	5	3.7
Easy set up (fixtures)	10%	3	3	3	4
Ease of maintenance	9%	3	3	3	2
TOTAL		1.375	4.62	4.26	3.59

5.2 Results and Discussions

Layout #1 (fig.5-2), received the highest score based on the evaluation criteria and weights in table 5-7. This was found best both in terms of material movement efficiency and area occupation, while generally modest performance with peer layouts in other criteria.

The following changes were suggested based on the above analysis, which brought us to select layout #1. These changes are shown pictorially in fig.5-3 below:

1) Drill usage is very minimal. So, remove the old drill machine or at least move it aside as shown in fig.10.

2) Move the CNC Chucker (1) and CNC Adapter (3) closer. This reduces walking time, material handling time and fatigue to worker.

3) Tap and Air test has low usage. Remove from the main flow or club inspection with it. This reduces footprint and space for WIP.

4) The S257 drill machine has couple of locations where it can be relocated as shown in the layout by red dots. The selected layout evaluated the more suitable location as shown in fig.5-2.

By implementing above suggested changes, as in the proposed layout #1,an expected savings of approximately 28.2 km in annual material movement, 89m per hour in walking distance, and 35.6 square meters in area occupied by cell will be observed.

In addition to this, as empty space is reduced from the cell, it's likely to have a reduction in WIP as well, as the saying goes "The more space you give, more will be the accumulation of inventory". Also, the cell occupied area along with material handling and walking time is reduced, which will lead to reduction in operator fatigue thereby increasing work efficiency.

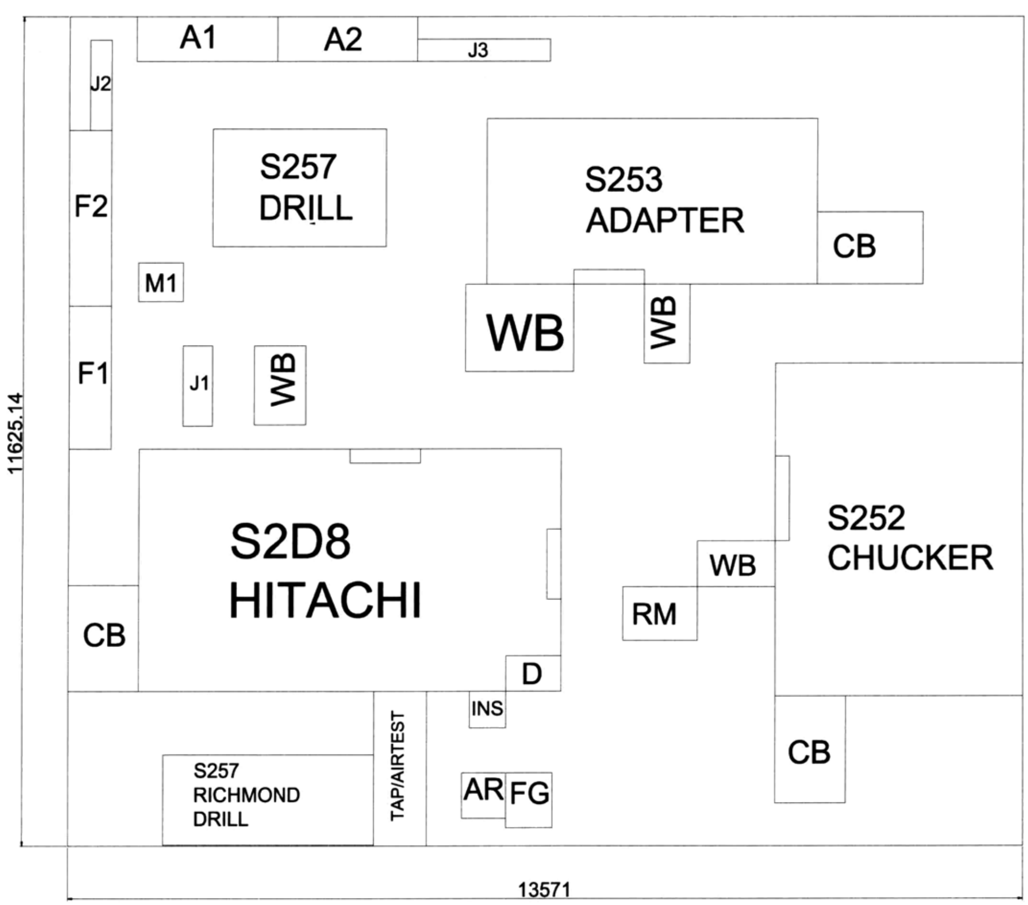

Figure 5-2: Selected Layout #1

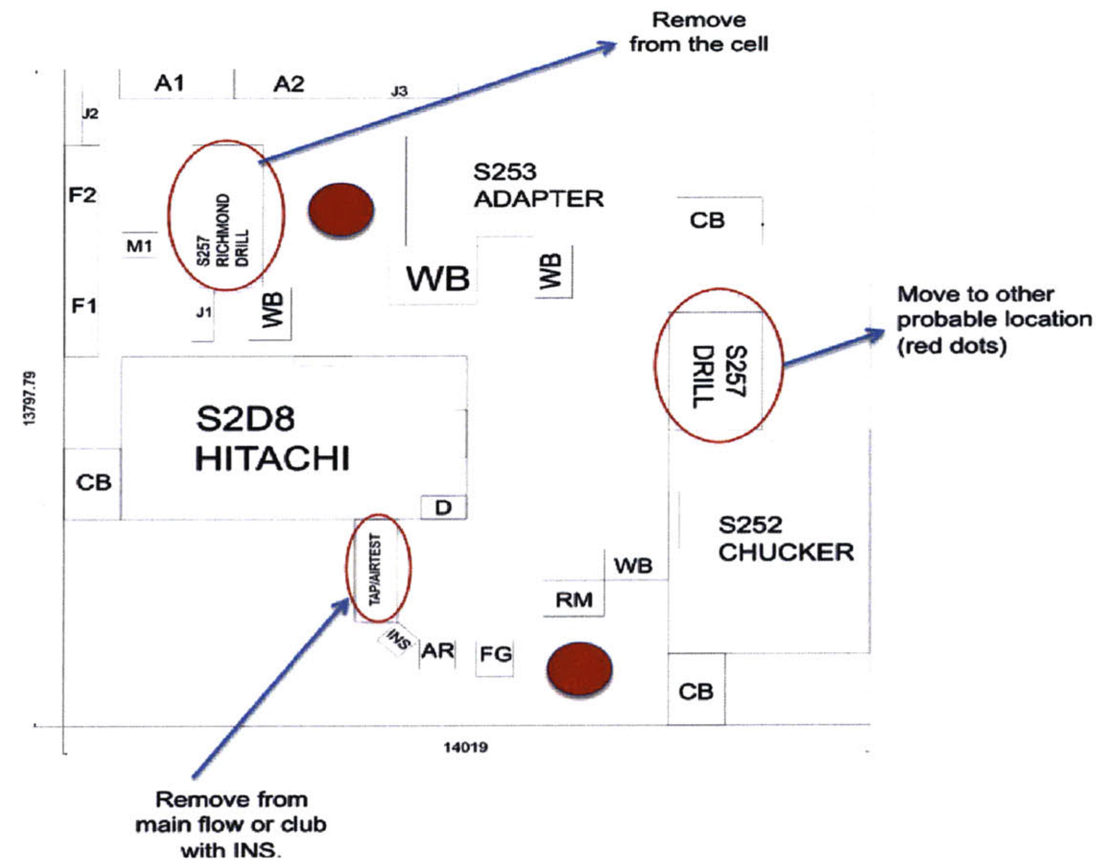

Figure 5-3: Suggested changes (from original)

5.3 Summary

After collecting data on the current layout of Head & Base Cell 1and later analyzing it, the team managed to understand the characteristics of the cell and thereby proposed several alternative layouts. Based on the evaluation criteria selected, we were able to evaluate the alternative layouts and select the best one with maximum improvements. In the selected layout design, 28.2 km in annual material movement, 89m per hour in walking distance, and 35.6 square meters in area occupied by cell were saved compared to the current layout.

Chapter 6: Value Stream Mapping: Protector Assembly

The following are the key topics of this chapter: -

- A review of current lean practices at Schlumberger.
- A discussion on Current VSM of protectors.
- A discussion on Future VSM of protectors.

6.1 Current Lean Practices at REDA Production Systems, Singapore

Schlumberger, Singapore started its quest to become Lean long ago. They have used in the past and are using value stream mapping as illustrated in Learning to see to implement Lean principles and techniques. Some of the Lean practices out of many they follow are:

1. Value Stream Mapping
2. Workplace organization.
3. Standardized Work
4. Flexible Operations/Cellular Manufacturing
5. Quick Changeovers
6. Implementing pull systems wherever possible
7. Visual Display Boards

Schlumberger follows continuous improvement practices as it works to make its manufacturing standards some of the world best.

6.2 Use of Value Stream Map to Improve Protector Assembly Process

In the past value stream map have been extensively used for improving processes in head and base machining and stage machining area. However, value stream mapping is not commonly utilized to streamline or improve assembly operations. This is possibly the first attempt to map the assembly process.

The value stream map here is created for one of the many products of REDA i.e. Protector. Protector has a number of different products within the category and the value stream map is prepared for the most common one i.e. Protector 540.There are variants within this protector 540 series based on number and types of chambers (illustrated in chapter 2) and shaft diameter.

The author himself collected this data, by visiting the shop floor and conducting time studies. The WIP data is obtained by counting the inventory between stages. The author believed that this way the data collected would be more reliable and trustworthy.
The purpose of this mapping process was to identify inefficiencies in the current state and to prepare a future state map with the aim of eliminating those inefficiencies and improving operational performance.

6.3 Interpreting the Protector Assembly Current Value Stream

The current state value stream map for the protector 540 is shown in fig.6-1.This value stream is representative of all the protector families except that the cycle times will differ. The summary statistics for the below current state map are dated June, 2009.

Before analyzing the value stream, the value stream needs to be understood, right from the material flow from left to right, to information flow from right to left. This value stream begins when all the parts required for assembly are delivered to the warehouse either from in-house manufacturing or outside vendors.

Warehouse & Pre-kit station

The planner issues a work order (WO) to the warehouse 3 day in advance of assembly. The warehouse operator picks one day worth of parts and supplies it to pre-kit station one day in advance of assembly. The pre-kit operator cleans the parts and puts them in a pre-kit box. These pre-kit boxes are then supplied to the assembly cell.

Sawing, Shaft Machining& Straightening

The shafts are made in-house. The raw material for shafts is in the form of long bars which are cut to size as per the work order at the sawing station. These shafts are then transported to the stacks where these are stored until picked for machining. The sawing station takes three days to supply the cut shafts to the next station once material is received from warehouse. The process parameters are summarized in figure 6-1.Next, the shafts are machined at the shaft machining station and those meant for assembly are sent for inspection while those for part sales are sent for packaging and finally shipping. The approximate inventory waiting time before the shaft machining station is 44.5 days. After inspection, the shafts are stacked on the stacks before the shaft straightening station where they are straightened to required tolerances. The approximate waiting time before shaft straightening is 23.2 days.

Assembly

The assembly operator picks the shaft from the stacks at the shaft straightening station. The approximate inventory waiting time after straightening is 2.17 days. The protector parts are then cleaned and assembled as per the drawing.

Oil fill &Test

All the protectors are then oil filled and tested at the oil fill & test station. The approximate waiting time is 0.5 days.

Welding, Blasting & Painting

After being filled with oil, the protectors are sent for welding. All the joints are welded. The approximate waiting time at welding station is 0.5 days. After welding the protectors are sent for blasting and panting. The approximate waiting time is 1.24 days.

Packaging& Shipping

After painting, the protectors are sent to packaging station where they are fitted with name plates and packaged in either metal or wooden boxes as required by the customer. The approximate waiting time here is 5.45 days. The packaged products are then picked and shipped by a third party vendor.

Information flow

The planners get customer demand from customer service department which they convert into weekly and daily production schedules based on First Come First Serve (FIFO) basis. The whole assembly shop is not controlled by one planner rather assembly operations are handled by several planners. There is lack of central scheduling system and scheduling is done mostly manually by planners. The planners monitor inventory in the warehouse and issue sales order for purchase from vendors.

6.4 Future Value Stream Map of Protector Assembly

The future value stream was creating by analyzing the current state map following methodology in [7].During the course of obtaining the answer to questions listed in section 3.2.4.2, several interviews with engineers, supervisors and operators were conducted. Apart from that the author himself observed the whole process by being on the shop floor for several days. The mapping process helped identifying and brought forward the problem areas in the value stream. These were classified into following two categories:

6.4.1 Lead Time reduction opportunities

1. Shortages of parts for assembly was identified as one of the major problems faced by the whole assembly facility irrespective of the product assembled. This on exploration presented the opportunity to optimize inventories in the warehouse taking stock inaccuracies into account. This has been discussed in detail in section 7.1.

2. The additional material handling between warehouse and head and base sub-assembly cell. This presented opportunity to eliminate the additional material handling by keeping the finished goods inventory at sub-assembly cell itself. Further it presents itself to test the

feasibility of implementing a Kanban[10] based pull system between warehouse, sub-assembly cell and pre-kit.

3. The shafts for the protector have long waiting times between the shaft machining and shaft straightening stage. These long waiting times add to customer lead-time and also increase inventory-holding costs. This presents opportunity for reducing WIP at this stage. This is discussed in detail in section 7.2.

4. A lack of information flow between planner, warehouse and assembly was also felt. Moreover the information flow was almost completely manual which adds to paper work time. Thus, a need was felt to promote better uses of IT to fasten the communications.

6.4.2 Process improvement opportunities

1. Incorrect material handling was identified. During material handling some parts like housing and body were getting their threads damaged. This posed problems during assembly. Operators had to do additional touching up operations before assembly that inadvertently increased assembly time.

2. Warehouse delivers parts required for assembly to pre-kit station. The pre-kit station cleans the parts and organizes the small parts into a wooden pre-kit box divided among a number of chambers. The operator doing the assembly depends almost entirely on this pre-kit box. If somehow the pre-kit operator misses to keep any item, there is every chance for the assembly operator to miss that in assembly as well. In current scenario, the parts are just dumped into the pre-kit box, increasing the probability of missing parts. This asked for an improvement in the pre-kitting procedure.

3. The assembly cell also needed a re-layout to ease the assembly and reduce waste in terms of unnecessary operator movements.

Corrective action: The assembly cell re-layout was done to eliminate the identified unnecessary operator movements.

4. For assembly and oil test (following the assembly), the actual timings do not match the routing timings and most of the times actual timings are much greater than the time allotted in routings. This forces operator at times to skip some steps (as listed in Manufacturing process instruction[11] manual (MPI)) or adopt ways, which are quicker or take less time. These might result in quality related issues if not checked.

Corrective action: To deal with the issue, several time studies were done for protector assembly and oil-fill & test stations predominantly and these were extended to all series of protectors. The time studies suggested that there was a gross mismatch between actual times and allotted

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[10] It is signaling device that gives authorization and instructions for the production or withdrawal of items in a pull system.

[11] MPI in short for Manufacturing Process Instructions is a list of "what to dos "and "how to dos" for the operators to follow while doing a manufacturing job.

timings. These revealed that for some protectors, actual time was found to be less while for others it was more than work order timings. The most common protector with highest demand had more than an hour of more time on routings, decreasing productivity. These findings were brought in knowledge of concerned people. The timings are now in the process of being updated to match actual timings.

5. The assembly operator needs to look at the drawing while doing assembly. The current protector assembly cell lacks place to properly secure the assembly drawing.

6. The bag for some protector types was checked for leak only at the clamped ends. The whole bag should rather be checked for leak.

7. The BOM attached with the drawing doesn't have the parts listed in a random fashion rather being in the same numbered sequence as in the drawing. This makes search for a particular part difficult.

Some of the above problems identified were resolved during the time horizon of this thesis while other were suggested by the author and may be considered later. All above improvements are depicted on future state map in fig.6-2.

6.5 Summary

This chapter summarized the use of value stream mapping at Schlumberger. A value stream map was used to analyze the current state of the protector assembly. Then by applying a set of Lean principles a future state map was created. The future state map has all the identified improvement opportunities depicted on it.

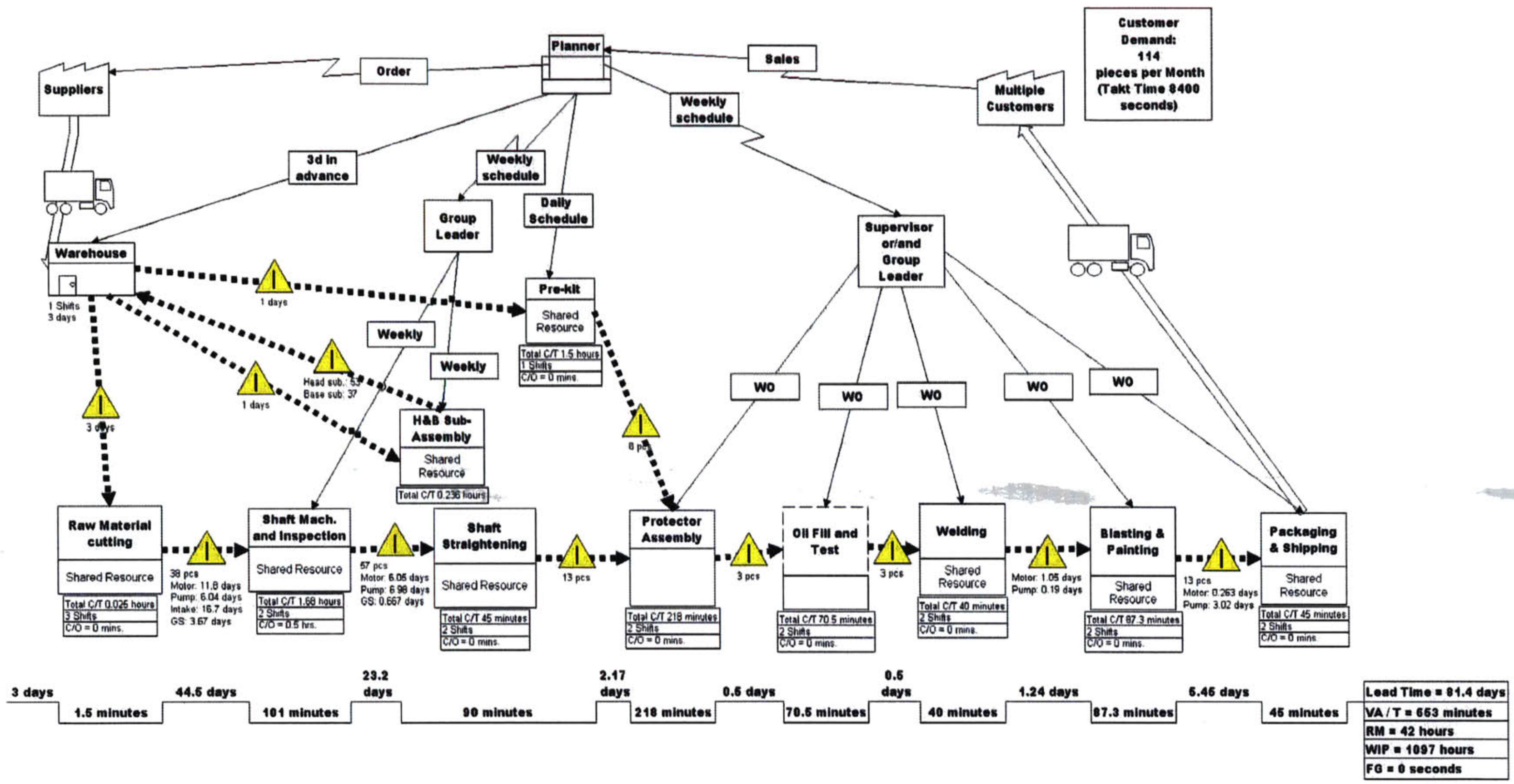

Figure 6-1: Current State Protector 540 Value Stream Map

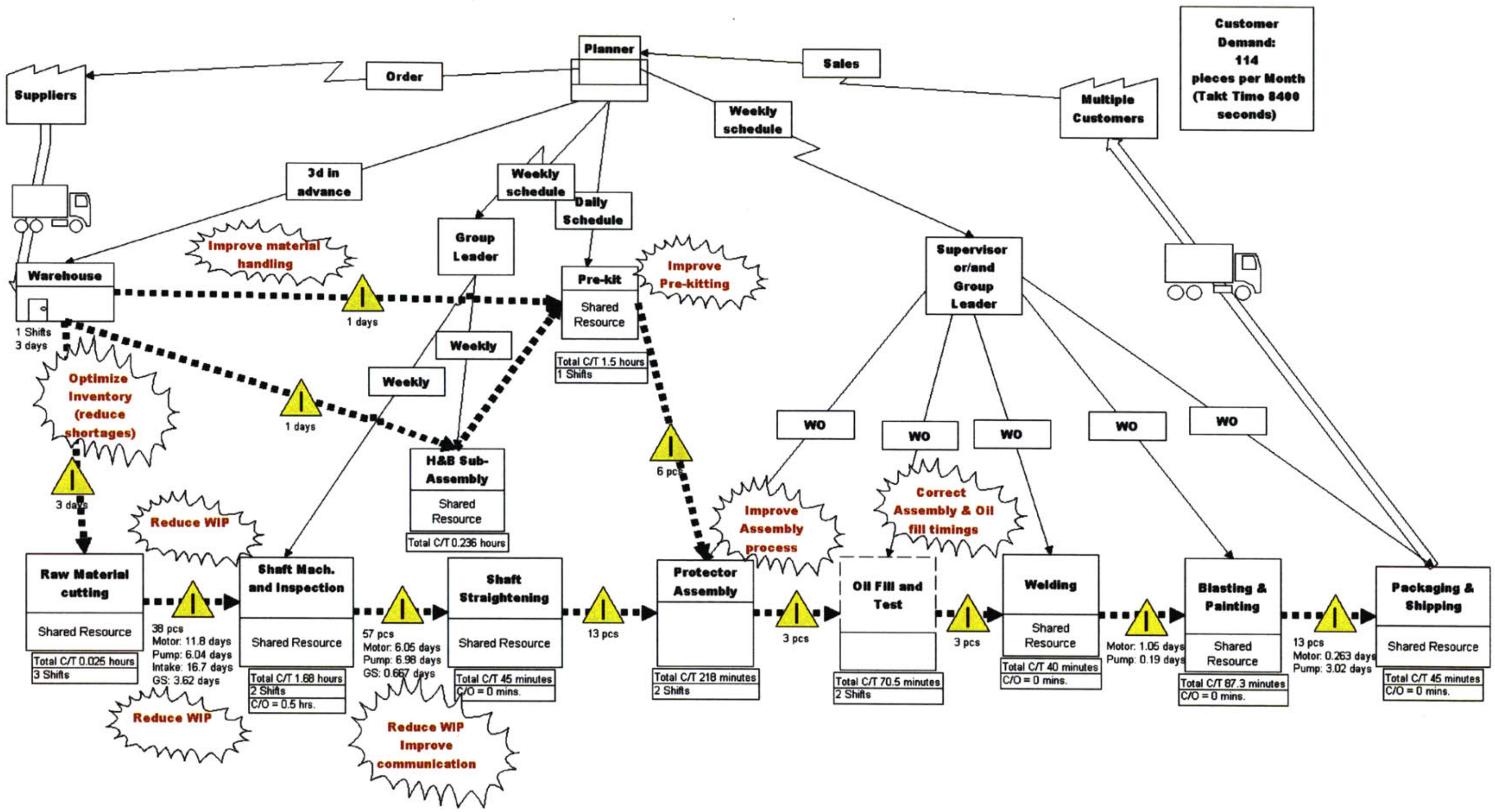

Figure 6-2: Future State Protector 540 Value Stream Map

Chapter 7: Future State Modeling: Protector Assembly

The following are the key topics of this chapter:

- A discussion of the impact of inventory inaccuracies on the system and methods for improving inventory accuracy
- A detailed simulation framework for compensating inventory inaccuracies
- Models to optimize safety stock in the warehouse
- A discussion of the need for improving scheduling

This is not to say that after successfully implementation of all the suggested changes an ideal state will be attained and no further improvements will be possible. All the processes will be completely reliable and free of any waste. Nothing is perfect and there is no real system than can attain an ideal state, so improvements will be needed consistently.

7.1 Inventory optimization

The current state map of the protector assembly value stream revealed that shortage of parts for assembly was a frequent phenomenon. The planner while issuing a work-order checks the available inventory in the system for the concerned parts. If the system shows sufficient inventory, the planner issues a work order to the warehouse to supply parts to assembly cell. But when the warehouse operator starts picking parts, he finds inventory absent for some parts and thus there occurs a shortage. The warehouse operator however delivers the remaining parts to assembly. The following reasons can be causing this:

1. The difference in the inventory record in the system and actual physical inventory or stock discrepancy or inventory inaccuracy. The sales order for a part is generated by the planners based on the inventory values in the system. Now, as a result of inventory inaccuracies the issue of sales order gets delayed and hence stock-outs occur leading to shortage of parts at the assembly. So, inventory inaccuracy is one of the causes of shortages.

2. The second reason is the suppliers' delays or delay at Quality control (QC). Thus, the time to warehouse (includes supplier lead time and time taken at QC) are variable, while system deals with lead times as deterministic, hence leading to stock-outs.

So, a solution to the above problems is needed to reduce shortages or stock-outs or to eliminate them. Some possible solutions are proposed to deal with the situation.

7.1.1 Inventory Inaccuracy

7.1.1.1 Causes of Inventory Inaccuracy

When there is a difference between an inventory record and actual physical inventory, inventory or stock inaccuracy is said to exist in the computerized system. This information is used for most decisions in the company like placing orders with the suppliers. Hence, lack of accuracy of the record can have serious implications for the business depending on the level of inaccuracy.

The causes that can be attributed to stock inaccuracies are many but some common ones are discussed as follows:

Stock loss, also known as shrinkage can occur because of several reasons. One reason can be theft. It can be both internal theft (operators) or external theft (visitors).Other reason can be the parts become outdated or they exceed their shelf life and hence become unusable.

Transaction error, for the case here can be at the inbound/incoming shipments at the facility. There can be discrepancy between the shipment record and actual shipment quantity, and if it goes unnoticed the inventory record will not reflect the actual stock accurately.

Inaccessible inventory are parts that are somewhere in the facility but cannot be found because the parts are absent from their assigned location. They might be spotted later but at the time of use they are not there. If parts are small they can sometimes be disposed as well, especially those parts that are stored at the shop floor and this may well lead to stock loss.

Apart from above, some of the causes of inaccuracy/stock inaccuracy are specific to the work company. A fraction of parts required for the assembly are stored at the shop floor. The remaining parts are stored at the warehouse and delivered on issue of work-order from the planner. The inventory stored locally at the shop floor has the issue of accountability. Also, management of inventory becomes difficult when it is stored at several locations. It may well be contributing to inventory inaccuracy.

7.1.1.2 Methods for reducing Inventory error

This section suggests some methods for reducing inventory error and thereby to reduce discrepancy between the inventory record and the actual physical inventory.

1. More the places of storage, difficult would be inventory control and higher may be the stock loss. The parts whose actual quantity required for assembly is known in advance should be stored at the warehouse itself, so that they can be better managed. For the protector assembly, apart from shim all parts have their actual quantity required known in advance. So, apart from shim everything should be stored and supplied by warehouse rather than locally by assembly.

2. Other methods can also be used to improve inventory accuracy in the system. One of the methods can be frequent labor intensive cycle counts. This will bring the inventory record to actual physical inventory and also might be able to draw attention towards some issues that might be causing inventory inaccuracy. Also, RFID tags can

be used for bigger parts like head and base, housing, bag and bag frame, shaft to keep an actual track of these.

However, it is difficult to eliminate inventory inaccuracy entirely from the system. Therefore, to upset/suppress the effect of inventory accuracy on the performance of the system, some compensation for inventory inaccuracy needs to be done. Yun Kang [15] deals this topic extensively and presents an excellent discussion of several compensating methods in detail. Each method is analyzed and their performance is compared by conducting simulation studies.

7.1.1.3 Inventory Inaccuracy Compensation Methods

This thesis suggests some of the compensating methods [15], which can be implemented by the company to deal with the existing inventory inaccuracy. However, some methods are applicable only to some parts.

Method 1 (IRP[12]): Safety stock is generally used to hedge against demand and supplier or in house lead time uncertainties. The safety stock prevents stock-outs on the cost of holding some additional inventory and thus additional investment. It can be further extended to hedge against inventory accuracy in the system.

The inventory policy followed by the company at present is (Q, R) policy. The order quantity is decided on the basis of past sales history for each part. The reorder point consists of expected demand during lead time and the safety stock[13]. Now, to compensate for inventory inaccuracy a higher safety stock, more than that required to hedge against demand and lead time variations, could be kept. This will increases the reorder point, leading to sales order released earlier than before and thus holding higher average inventory providing shield against inventory inaccuracy.

At present, the company commits a Type I service level [14]of 95% (or 99.80 % Type II service level[15]) to its customers. Due to shortages; however this service level is not achieved. So, to hedge against inventory inaccuracies and achieve 95 % service level, safety stocks and hence reorder point can be increased. This will lead to higher inventory and will prevent stock-outs in spite of stock inaccuracy.

To find the new reorder point that helps upset effects of stock inaccuracy on system, a simulation study was conducted using Crystal ball simulation software. This method by increasing the reorder point maintains excess inventory in the system. Thus higher inventory on hand subdues stock inaccuracy effects. However, the excess inventory means higher investment. But for the case here most of the items causing shortages are small and cheap items which even if stored in large quantities will not involve a huge investment. This method however is not suitable for high stock inaccuracies.

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[12] Increasing Reorder point

[13] Safety stock is additional inventory held to protect against demand and/ or lead time uncertainties.

[14] This reflects the number of stock-outs events allowed in a given no of replenishment cycles.

[15] This not only reflects the stock-out events but also the amount back-ordered in each stock-out event.

Method 2 (CDR[16]): This method involves a constant decrement in inventory record. If the inventory/stock discrepancy and its stochastic behavior are known, another method of compensating for inventory inaccuracy can be a constant decrement in the inventory record by the average stock discrepancy each period. However, since the actual value of error is still unknown; simply decrementing the record there will not eliminate the error in the inventory record. However, this compensation can be expected to perform better than no compensation at all.

Method 3 (IRP & CDR): This method is a combination of above discussed two methods. First, an average stock discrepancy each period is deducted from the inventory record. Since the actual value of error is still unknown; simply decrementing the record will not eliminate the error in the inventory record. Hence, the safety stock is increased to hedge against this uncertainty.

Stochastic simulation model of the three methods

A simulation study to compare the above three illustrated inventory inaccuracy compensation methods was conducted using crystal ball simulation software. The study aimed at calculating the optimum levels of the reorder point where required and at the same time compare the performance of the suggested methods.

The simulation model comprised of following characteristics and parameters:

1. The purchase demand during each period i, d_i, was independent and normally distributed with mean μ_d and standard deviation σ_d. As demand can't be negative, so a truncated normal distribution was used with all the negative demands ignored.

2. The stock loss in each period i, s_i, was also independent and identically distributed, and was generated from a Poisson distribution having mean λ.

3. The lead times, L, was independent and normally distributed with mean μ_L and standard deviation σ_L.

4. The demand that occurred when there were zero actual on-hand inventories was recorded as backlog and fulfilled when order quantity arrived.

A Poisson distribution is chosen for stock loss in order to prevent the distribution assigning negative values to stock los if mean of distribution is small.

The sequence of events in order of occurrence each period was:

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[16] Constant Decrement in Inventory Record

1. The inventory record was reviewed and an order was placed if the inventory was equal or below reorder point.
2. The incoming order (if any) was received.
3. Sales and stock loss took place.

Let x_i, Q_i be the inventory and the incoming order quantity at the beginning of period i. Thus x_i+Q_i was available to meet the purchase demand and stock loss in period i. When the sum of incoming demand and stock loss exceeds the available inventory, the excess is recorded as backlog in the system. This backlog would be served from the next incoming order.

$$x'_{i+1}=x'_i + Q_i - d_i \tag{7.1}$$

$$x_{i+1}=x_i + Q_i - d_i - s_i \tag{7.2}$$

The equations above denote inventory record (eq^n. 7.1) and actual physical inventory (eq^n. 7.2) each period respectively. Since inventory record doesn't see stock loss hence stock loss term s_i, is absent from eq^n. 7.1.

The demand and lead times are stochastic in the model so the safety stock is sized accordingly. This is to say that the safety stock covers uncertainty both in demand and lead times. However, for the simulation the mean lead time, μ_L is used. The orders are placed by comparing the inventory record (x_i') with reorder point while demand and stock loss is met by actual physical inventory (x_i).

7.1.1.4 Results and Discussions

A sample simulation was run with the purpose of comparing the performance of above three methods. The average demand μ_d is 10 and the standard deviation σ_d is 3.The average daily stock loss λ is varied from 1% to 7% (or 0.1-0.7), of the average daily demand. The average lead time μ_L is 3 days and the standard deviation σ_L is 0.5 day. The fixed order quantity Q is 40.The operation time is 365 days as every company performs a physical count at least once a year, where the inventory record is adjusted to match the physical inventory. The initial inventory is Q+SS[17] (or R+Q- μ_d μ_L).The company commits a service level of 99.80% type II service level to its customers that means it allows 0.2% stock-out rate – defined in terms of the total lost sales with respect to demand over the operating period (which accumulates here as backlog which will be transferred to the next operating period).This is the target stock-out rate and the corresponding reorder point is R= 45 used in simulations where stock loss occurs. The increase in stock-out rate (SR) with average daily stock loss λ varied from 0% to 7% of average daily demand is shown in fig.7-1 and tabulated in table 7-1.Each of the data points is a result of 2000 independent simulation runs.

[17] SS-Safety stock

Table 7-1: Increase in backlog with rise in inventory inaccuracy

S.No.	Stock Inaccuracy (%)	Accumulated Backlog (%)
1	**0**	0.20
2	1	5.73
3	2	17.07
4	3	29.29
5	4	41.79
6	5	52.62
7	6	60.16
8	7	66.32

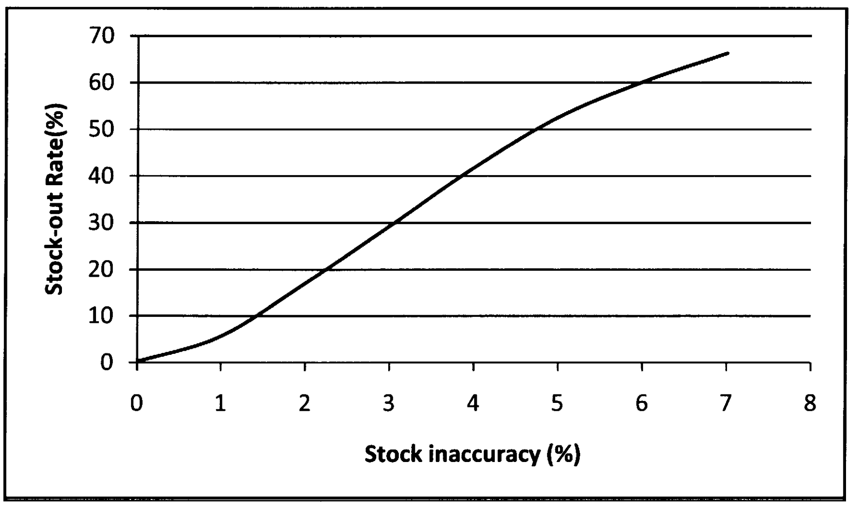

Figure 7-1: Stock-out rate vs. Stock inaccuracy (no compensation)

The fig. 7-1 emphasizes the importance of knowing the accurate inventory. In absence of accurate information about inventory , it is evident that stock inaccuracy severely impacts the system performance. When the stock loss is zero, the system achieves its target stock-out rate of 0.2% (or 99.80 % type II service level).When the stock loss increases, the error in inventory record grows and leads to rise in increasing backlog (or lost sales).Soon after the stock loss of 1% is surpassed, the stock-out curve grows steeper. With stock loss as low as 2% of average demand, the stock-out rate rises to around 17%.This clear indicates that in the absence of any corrective action, even small stock discrepancy can severely hamper the system performance. The performance parameters of the three compensation methods are compared with no compensation case in table 7-2.Fig.7-2 shows the stock-out rate achieved when either of the compensating methods is implemented.

Table 7-2: Comparison of Inventory Inaccuracy Compensation Methods

S.No.	Stock inaccuracy (%)	No compensation		Method 1 (IRP[18])		Method 2 (CDR[19])		Method 3 (CDR & IRP)	
		R	AB[20] (%)	R	AB (%)	R	AB (%)	R	AB (%)
1	0	45	0.20	45	0.2	45	0.20	45	0.2
2	1	45	5.73	73	0.2	45	0.25	46	0.2
3	2	45	17.07	108	0.2	45	0.39	48	0.2
4	3	45	29.29	144	0.2	45	0.58	50	0.2
5	4	45	41.79	180	0.2	45	0.69	53	0.2
6	5	45	52.62	215	0.2	45	0.93	55	0.2
7	6	45	60.16	252	0.2	45	1.02	57	0.2
8	7	45	66.32	289	0.2	45	1.27	59	0.2

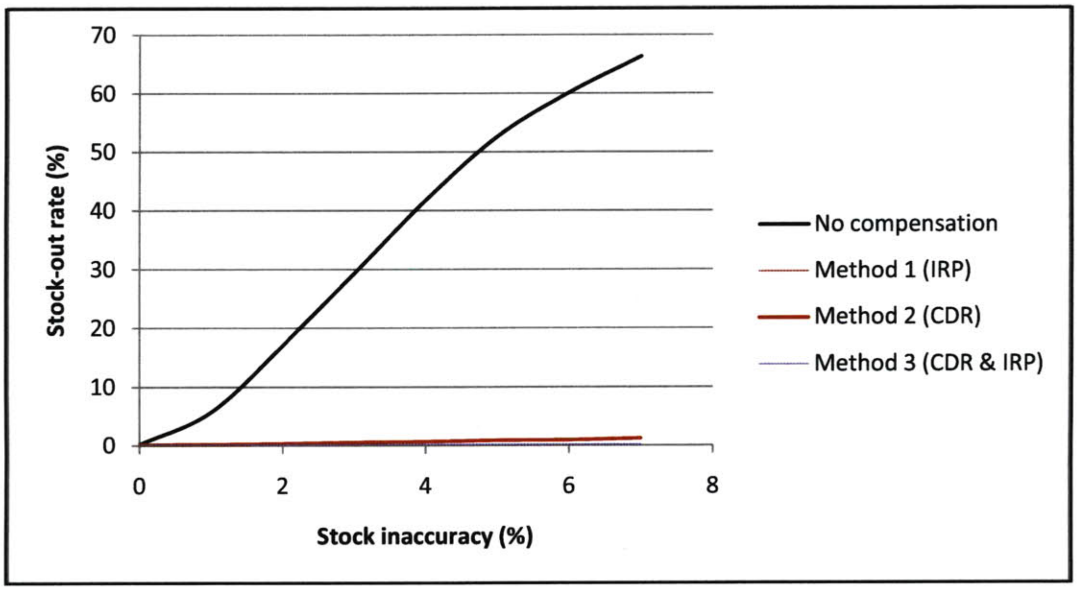

Figure 7-2: Stock-out rate vs. stock inaccuracy (compensating methods compared)

The "No Compensation" column in table 7-2 shows the case when no corrective action is taken to reduce impact of inventory error on system performance.

For each value of average stock loss λ, in method 1 the reorder point R is varied in steps of 1 around base value 45 such that target stock-out rate of 0.2% is achieved. With inventory error as small as 1% of average daily demand, the reorder point must be increased to 73 to maintain target stock-out rate of 0.2%, which means we end up holding additional safety stock worth 3 days worth of average demand. This rise in safety stock

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[18] Increasing Reorder point

[19] Constant Decrement in Inventory Record

[20] Accumulated backlog over a period of 365 days (1 year)

grows further with increasing inventory error to 144 i.e. approx. 10 days of average demand at 3% error to 289 (additional safety stock worth 24.5 days of average demand) at 7% error. Hence, this clearly indicates at higher values of inventory error or stock loss the additional inventory needed to maintain target stock-out rate becomes prohibitive. To conclude, this method is suitable at only low values of stock loss may be less than 2% of average demand.

The method 2 which involves decrementing the inventory record by the average stock loss performs comparatively much better than merely increasing the reorder point. The performance is remarkably better and reduces the stock-out rate however; simply reducing a constant value from the inventory record each period doesn't serve the purpose to the fullest. With inventory error growing to as much as 7% of average demand we can see the stock-out rate rises to 1.27% which is several times higher than the target stock-out rate of 0.2%.

The method 3 is a combination of the two previous methods 1&2. Apart from decrementing the inventory record by the average stock loss each period, it also increases the reorder point. Fig. 7-3 reveals that the rise in reorder point required to achieve the target stock-out rate of 0.2% is much less in methods 3 in comparison to method 1.Also as evident from fig.7-2 method 3 also performs better in achieving the target stock-out rate in comparison to method 2. Hence, method 3 clearly outperforms the other two methods by overcoming their shortcomings and striking a suitable combination of the two to achieve the target stock-out rate as apparent from table 7-2 and figures 7-2 and 7-3.

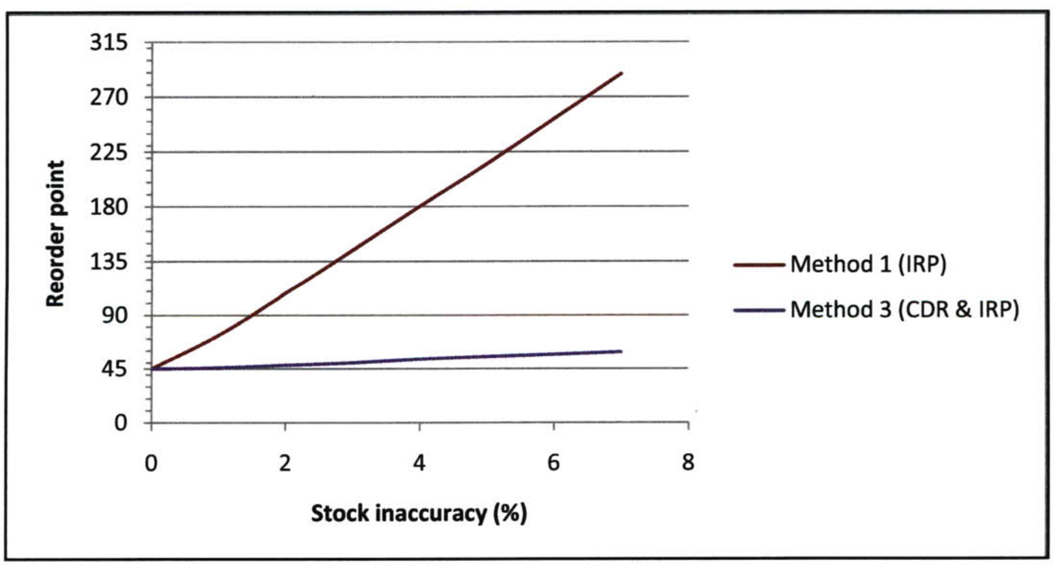

Figure 7-3: Rise in reorder point to shield against stock inaccuracy

To conclude, any of three methods can be implemented as a compensation for inventory inaccuracy though method 3 comes out the best of all three compensation methods discussed here. The snapshots of the crystal ball simulation spreadsheets are attached in Appendix D, fig D-1 to D-2 for reference.

7.1.2 Safety Stock

Inventory is indeed very important for parts bought from outside vendors if the lead time is some finite number other than zero. The inventory is comprised of two components, cycle stock and safety stock. The inventory has to meet period demand as well as it has to provide shield against demand and lead time uncertainties. If demand and lead times (internal or external) are completely deterministic then there is no need to keep any safety stock. However in real environments, demand and lead times are generally stochastic. However, if the variation in demand and lead times is small then they can well be assumed deterministic but if the variations are large demand and lead times should be treated as stochastic. The literature in [16] deals the following two situations separately:

Case 1: The first case deals with the situation when demand is stochastic while lead times are deterministic. In this case, safety stock is needed just to shield against demand variations during lead time. The safety stock calculations can be done by using model in eq^n.1 below. The model below assumes normal demand which is a valid assumption in most real cases.

Let μ_d and σ_d be the mean and standard deviation of demand per unit time. The expected demand can be calculated as:

$$E(D) = \mu_d L \qquad (7.3)$$

$$\text{Safety Stock (SS)} = \text{safety factor } (k) * \text{sigma } (\sigma_d) * \text{lead time } (L)^{1/2} \qquad (7.4)$$

$$\begin{aligned} \text{Reorder point} &= \text{Expected demand during lead time} + \text{Safety stock} \\ &= E(D) + SS \\ &= \mu_d L + k\,\sigma_d \qquad (7.5) \end{aligned}$$

Where k - safety factor is an index or measure of service level a company commits to its customer. The above formula assumes normal demand which is a valid assumption in most cases.

From normal table
k = 1.64 provides 0.95 coverage probability
k = 2 provides 0.98 coverage probability
k = 3 provides 0.999 coverage probability

σ - Standard deviation of demand (assumed normal) from mean.
L – Lead time i.e. the time to replenish inventory once an order is placed.

Case 2: This case deals with the situation when both demand and lead times are stochastic. Here, safety stock is needed to shield against both demand variations during lead time and lead time variations. The safety stock calculations can be done by using model in eq^n.2 below. The model assumes normal distribution of demand during stochastic lead times.

Let μ_d, σ_d & μ_L, σ_L be the mean and standard deviation of demand per unit time and lead time respectively. The expected demand and variance in demand then can be calculated as:

$$E(D) \text{ or } \mu'_d = \mu_d \mu_L \tag{7.6}$$

$$\text{Variance of Demand, Var (D) or } \sigma'_d = \sigma_d^2 \mu_L + \mu_d^2 \sigma_L \tag{7.7}$$

$$\text{Safety Stock (SS)} = \text{safety factor (k)} * \text{sigma } (\sigma'_d) \tag{7.8}$$

$$\begin{aligned} \text{Reorder point} &= \text{Expected demand during lead time} + \text{Safety stock} \\ &= E(D) + SS \\ &= \mu_d \mu_L + k\, \sigma'_d \end{aligned} \tag{7.9}$$

Where k- safety factor

At present the company is using model discussed in case 1 (stochastic demand, deterministic lead times) for its safety stock calculations. However, discussion with the personnel handling suppliers, revealed the fact that lead times for some components involved large variations and the situation actually resembled case 2 rather than case 1. A snapshot of the excel spreadsheet with embedded formulae created for the company is attached in Appendix E, fig. E-1.

7.2 Production Scheduling

After the inventories were corrected and general operational methodology is established the production steps still needs to be coordinated. The incoming raw material, transformation of raw material into final product and shipping to customer needs to be synchronized. This requires proper scheduling of all processes across the value stream.

The entire value stream for product is shown in fig.6-1. Different stages of value stream are handled by different planners. The scheduling process is mostly manual and neither MRP nor any other scheduling tool is used. The planners do production scheduling based on experience. Also, there is minimal to no coordination between different planners. The map shows high WIP between raw material cutting and shaft machining & shaft machining and shaft straightening stages.

The shafts machined at shaft machining station, are both used by assembly and sold separately as well. The machining station makes hundreds of different shafts which differ in diameter and length, material and machined features. The changeover time for machining is of the order of 30 minutes. Manual scheduling at this station with such a huge variety is itself very difficult.

The shaft straightening is a manual process and doesn't involve any changeovers. The shafts which meant for assembly goes for shaft straightening after machining. While those for sales, are packed and shipped after machining. The customer demand for both stations hence differs. The scheduling for shaft machining and shaft straightening is handled by different planners. Both planners do scheduling for their respective stations with no coordination between them. This results in long waiting times at these stations.

This lack of any central knowledge base reflecting current situation has led to other problems as well. The planners at times, place duplicate orders for the same piece of buy part, and these duplicate work orders are processed separately. So, they end up ordering twice or thrice or more quantities and thus unknowingly increase inventory.

The above scenario thus clearly asks for a better use of existing MRP systems and also using them or some other production scheduling tool to perform all the scheduling jobs in the facility. This will ensure that operations are smooth and the stations work in co-ordination rather than in isolation. The idea is to have a centralized knowledge base which could contain all information and use of it to do scheduling and ordering decisions.

7.3 Summary

Inventory inaccuracy, can degrade the system performance if it goes unnoticed. So as means of corrective action three compensation methods were discussed and their performance was compared, using simulation. The method 3 which works by decrementing the inventory record by average stock loss each period and increasing the safety stock (and thus reorder point) to ensure that target stock-out rate is achieved performed best out of the three compensation methods discussed here. If applied, it will prevent the impact of inventory error on the system performance. However, one may choose to use other methods as well. This chapter also presented the approach to calculate the safety stocks in case of either deterministic or stochastic lead times with stochastic demand. The need of having a central scheduling system was also emphasized to aid in scheduling so as to ensure a smooth flow across the facility.

Chapter 8: Conclusions & Recommendations

Motivated by the aim of improving operational performance an analysis of cell layout was done. By implementing the changes suggested in following section 10.1, the results suggest that considerable improvements in material handling and walking times and cell occupied area can be achieved. Moreover, as a result better work efficiency and enhanced productivity can also be achieved.

The value stream map for protector assembly was motivated with identifying inefficiencies in the protector value stream. The current value stream map revealed several inefficiencies in the value stream, improving which can lead to significant reductions in lead time and improvements in protector assembly process. However, some of the problems highlighted by the value stream map needed further analysis beyond the scope of value stream map.

Shortages of items to assembly were one of biggest problems identified. The reasons identified were inventory inaccuracy and inadequate safety stock. Three compensating methods for inventory inaccuracy were suggested and their performance was compared using a stochastic simulation. The simulation results suggested that in case of no compensation of inventory inaccuracy the system performance is severely affected.

The simulations results demonstrated that the classic way of buffering against operational uncertainties by carrying the safety stock is indeed not feasible because of prohibitive rise in inventory. Other methods tested were decrementing the inventory record by a constant stock loss value each period. The performance is remarkably better and reduces the stock-out rate however; simply reducing a constant value from the inventory record each period doesn't serve the purpose to the fullest. Hence finally a combination of these two discussed methods was tested which maintains the target stock-out rate and at the same time the rise in safety stock is minimal. This method thus outperforms the other two methods.

The recommendations for the company are summarized below:

8.1 Cell Re-layout

The analysis of the existing cell layout had shown way to changes that can significantly improve the operating performance of the cell and enhance productivity. The following changes are suggested as a result of this study:

1. Drill usage is very minimal. So, remove the old drill machine or at least move it aside as shown in fig.5-2.

2. Move the CNC Chucker (1) and CNC Adapter (3) closer. This reduces walking time; material handling time and fatigue to worker (see fig.5-2&5-3).

3. Tap and Air test has low usage. Remove from the main flow or club inspection with it. This reduces footprint and space for WIP (see fig.5-2&5-3).

4. The S257 drill machine has couple of locations where it can be relocated as shown in the layout by red dots.

The benefits obtained by implementing above recommended changes were significant as discussed in section 5.2.

8.2 Protector assembly

The current value stream map revealed several inefficiencies within the protector assembly value stream. These if eliminated can significantly improve the performance of the product value stream. Some problems are so general that if corrected they will improve the performance of all the products' value streams. The recommendations can be summarized as follows:

1. The head and base parts instead of going back to warehouse after sub-assembly operations should rather be delivered to the subassembly cell one day before final assembly along with other parts to pre-kit. During the day the head and base will undergo sub-assembly operations. Later, then can be picked by the pre-kit operator and delivered to assembly cell. By doing this, additional material handling step is eliminated and also waiting time of head and base subassemblies is reduced to minimal.

2. The study revealed that shortage of parts to assembly is caused by stock inaccuracy and inadequate safety stock to hedge against demand and lead time uncertainties. To reduce this following steps are suggested:

I. First, the part demand and lead times are both found to be stochastic, so the safety stock calculation should be revised and should be done by using the model suggested in section 7.1.2 case2.

II. Second, the fraction of parts for assembly which are stored locally at assembly should be shifted back to warehouse except shims. This will promote better management of the inventory thereby decreasing inventory inaccuracies.

III. However, stock inaccuracies are still present in the system and to subdue their impact on system performance, this study suggests three compensation methods in section 7.1.1. Once stock inaccuracy data is on hand either of the compensating methods suggested can be used though method 3 is best of all the three and is strongly recommended.

3. The shafts for the protector have long waiting times between raw material cutting and shaft machining & shaft machining and shaft straightening stages. These long waiting times can be attributed to manual scheduling of each station independently by different planners, preventing smooth flow between stations and increasing WIP. Hence some central scheduling system like MRP or other scheduling software should be used for the purpose.

4. A major part of information flow was found to be manual which adds to paper work time. The company should strive to make better use of IT and the paper work to the extent possible should be made electronic.

5. While observing the assembly process some shortcomings were spotted and following are the recommendations regarding process improvements.

I. For some parts like housing and body incorrect material handling was identified that damaged the threads and needed some touch up operations on the operator's part. So, handling methods need to be improved for the concerned parts.

II. The pre-kit station cleans the parts and organizes the small ones into a wooden pre-kit box divided among a number of chambers. The assembly operator depends almost entirely on this pre-kit box. In case of a part miss from the pre-kit, there is every chance for the assembly operator to miss that while assembly. Currently, the parts are just dumped into the pre-kit box, increasing the chance of missing parts. So, the pre-kitting procedure needs an improvement. Every part going in the pre-kit box should have a clearly labeled section allocated to it and it should be secured at allocated place only while pre-kitting. This will make the whole procedure more transparent and will reduce the chance of a miss part.

III. All the assembly and oil-fill routings need to be updated to reflect the correct operation times as suggested by the multiple time studies done by the author. This will increase productivity on one hand as the most common protector with highest demand had more than an hour of more time on routings. On the other hand improve quality and motivate workers to adhere to MPI where less time for operation forced the operator at times to skip some steps (as listed in Manufacturing process instruction manual (MPI)) or adopt ways, which are quicker or take less time.

8. The assembly cell should include a place for the operator to hook the assembly drawing as he needs to look at it during assembly

9. The bags for some protector types were checked for leak only at the clamped ends. The whole bag should rather be checked for leak.

10. The BOM attached with the drawing should have the parts listed in the same sequence as depicted on the drawing. This makes search for a particular part easier.

Chapter 9: Future Work

Future work in area of cell layout analysis would be scheduling the head and base production in cell 1.An optimized scheduling will help reduce set-ups and thus improve productivity.

Value stream mapping of protector assembly revealed high WIP at shaft machining and shaft straightening stages. Future research could look into optimizing scheduling of shaft machining and shaft straightening stations in order to ensure smooth flow and reduction in WIP.

A detailed framework to deal with inventory inaccuracy though was provided, but further work could be to resolve practical issues and actually implement the best possible solution.

This research concentrated on optimizing the safety stocks either to hedge against lead time uncertainties or stock inaccuracy. However, during the course of this work it was observed that the methodology to decide on order quantity in use is naïve; hence future research can concentrate on optimizing the order quantity.

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Appendix A: Value Stream Symbols

Value Stream Mapping symbols are not standardized and there are many variations. Here are the most common symbols. The VSM icons are divided into four categories: Process, Material, Information and General symbols. The list below is not exhaustive and there are other symbols used, some are made to use by individuals.

Table A-1: VSM Process Symbols

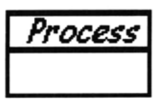
 **Customer/Supplier**	This icon represents the Supplier when in the upper left, the usual starting point for material flow. The customer is represented when placed in the upper right, the usual end point for material flow.
 **Dedicated Process**	This icon is a process, operation, machine or department, through which material flows. Typically, to avoid unwieldy mapping of every single processing step, it represents one department with a continuous, internal fixed flow path. In the case of assembly with several connected workstations, even if some WIP inventory accumulates between machines (or stations), the entire line would show as a single box. If there are separate operations, where one is disconnected from the next, inventory between and batch transfers, then use multiple boxes.
 **Data Box**	This icon goes under other icons that have significant information/data required for analyzing and observing the system. Typical information placed in a Data Box underneath FACTORY icons is the frequency of shipping during any shift, material handling information, transfer batch size, demand quantity per period, etc. Typical information in a Data Box underneath MANUFACTURING PROCESS icons: · C/T (Cycle Time), C/O (Changeover Time) Uptime
 **Work-cell**	This symbol indicates that multiple processes are integrated in a manufacturing work cell. Such cells usually process a limited family of similar products or a single product. Product moves from process step to process step in small batches or single pieces.

Table A-2: VSM Material Symbols

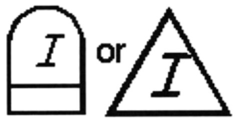
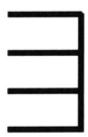
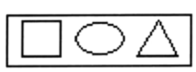
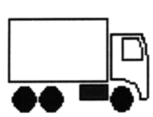
 **Inventory**	These icons show inventory between two processes. While mapping the current state, the amount of inventory can be approximated by a quick count, and that amount is noted beneath the triangle. If there is more than one inventory accumulation, use an icon for each. This icon also represents storage for raw materials and finished goods.
 **Shipments**	This icon represents movement of raw materials from suppliers to the Receiving dock/s of the factory. Or, the movement of finished goods from the Shipping dock/s of the factory to the customers
 **Push Arrow**	This icon represents the "pushing" of material from one process to the next process. Push means that a process produces something regardless of the immediate needs of the downstream process.
 **Supermarket**	This is an inventory "supermarket" (Kanban stock point). Like a supermarket, a small inventory is available and one or more downstream customers come to the supermarket to pick out what they need. The upstream work center then replenishes stocks as required.
 **Material Pull**	Supermarkets connect to downstream processes with this "Pull" icon that indicates physical removal.
 **Or**  **FIFO Lane**	First-In-First-Out inventory.
 **Safety Stock**	This icon represents an inventory "hedge" (or safety stock) against problems such as downtime, to protect the system against sudden fluctuations in customer orders or system failures.
 **External Shipment**	Shipments from suppliers or to customers using external transport. Different icons depict mode of transportation.

Table A-3: VSM Information Symbols

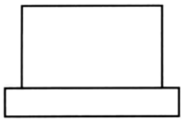
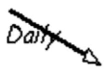
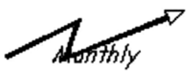
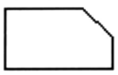
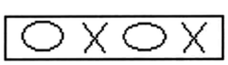
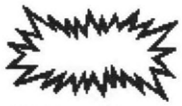
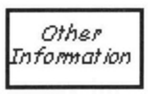
 **Production Control**	This box represents a central production scheduling or control department, person or operation.
 **Manual Info**	A straight, thin arrow shows general flow of information from memos, reports, or conversation. Frequency and other notes may be relevant.
 **Electronic Info**	This wiggle arrow represents electronic flow such as electronic data interchange (EDI), the Internet, Intranets, LANs (local area network), WANs (wide area network). You may indicate the frequency of information/data interchange, the type of media used ex. fax, phone, etc. and the type of data exchanged.
 **Production Kanban**	This icon triggers production of a pre-defined number of parts. It signals a supplying process to provide parts to a downstream process.
 **Withdrawal Kanban**	This icon represents a card or device that instructs a material handler to transfer parts from a supermarket to the receiving process. The material handler (or operator) goes to the supermarket and withdraws the necessary items.
 **Signal Kanban**	This icon is used whenever the on-hand inventory levels in the supermarket between two processes drops to a trigger or minimum point. When a Triangle Kanban arrives at a supplying process, it signals a changeover and production of a predetermined batch size of the part noted on the Kanban. It is also referred as "one-per-batch" Kanban.
 Kanban Post	A location where Kanban signals reside for pickup. Often used with two-card systems to exchange withdrawal and production Kanban.
 **Sequenced Pull**	This icon represents a pull system that gives instruction to subassembly processes to produce a predetermined type and quantity of product, typically one unit, without using a supermarket.
 **Load Leveling**	This icon is a tool to batch Kanban in order to level the production volume and mix over a period of time
 **Go See**	Gathering of information through visual means.
 **Phone**	Shows information flow between two via phone.

Table A-4: VSM General Symbols

 **Kaizen Burst**	These icons are used to highlight improvement needs and plan kaizen workshops at specific processes that are critical to achieving the Future State Map of the value stream.
 **Operator**	This icon represents an operator. It shows the number of operators required to process the VSM family at a particular workstation.
 **Other**	Other useful or potentially useful information.

Appendix B: Acme Value Stream Maps

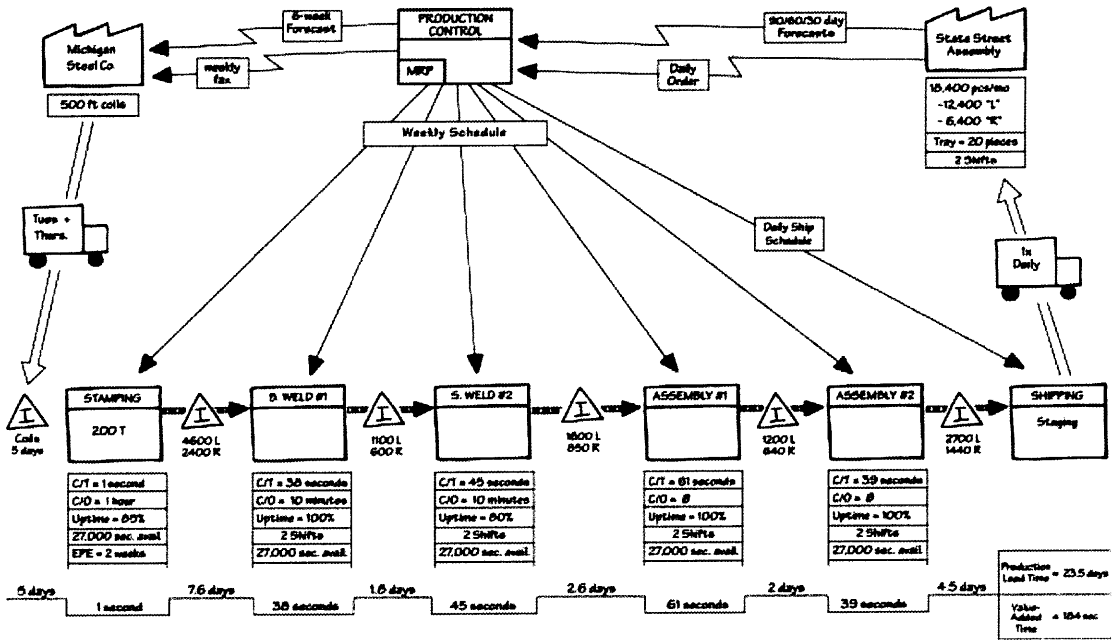


Figure B-1: Acme Current Value Stream Map

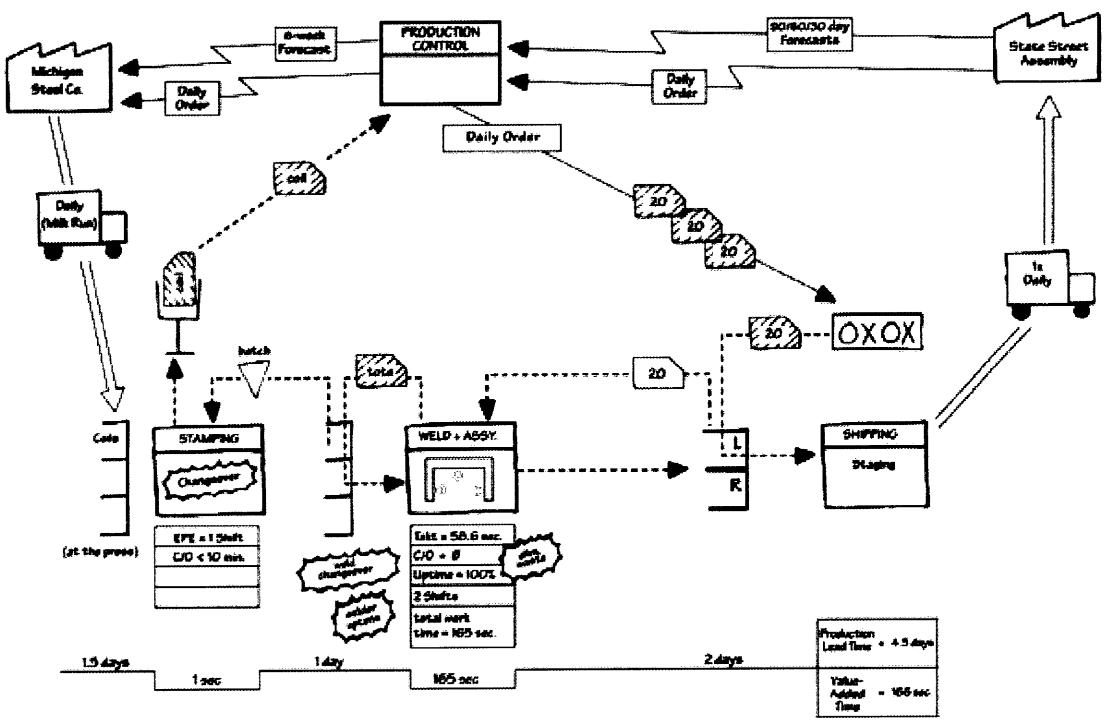


Figure B-2: Acme Future Value Stream Map

Appendix C: Cell layouts

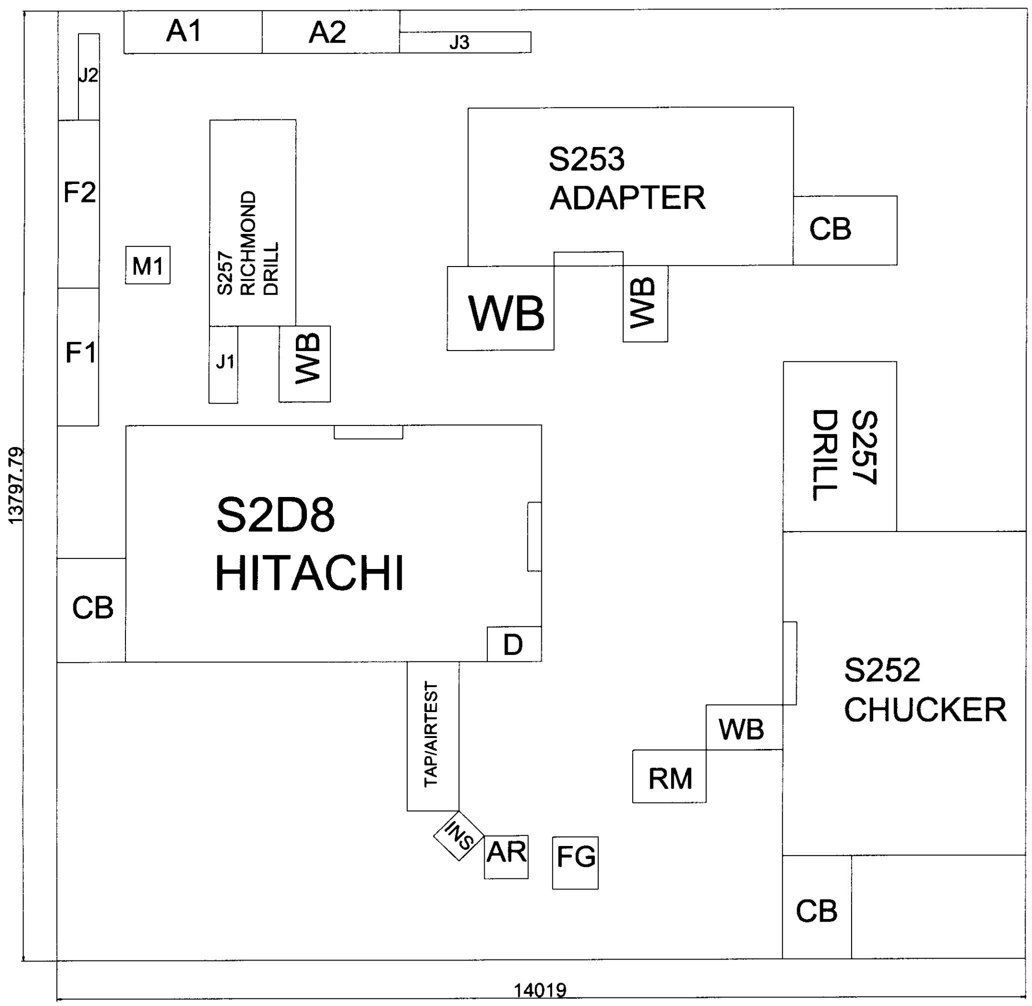


Figure C-1: Current Layout

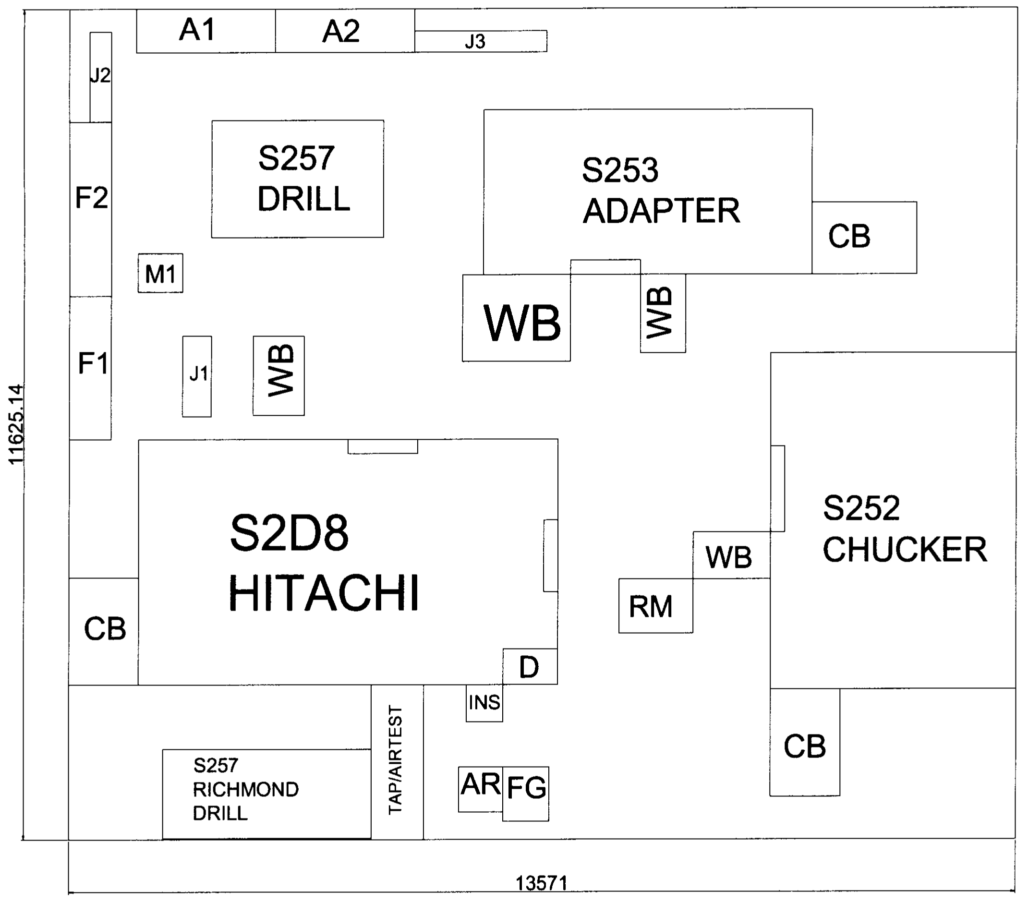


Figure C-2: Layout Concept 1

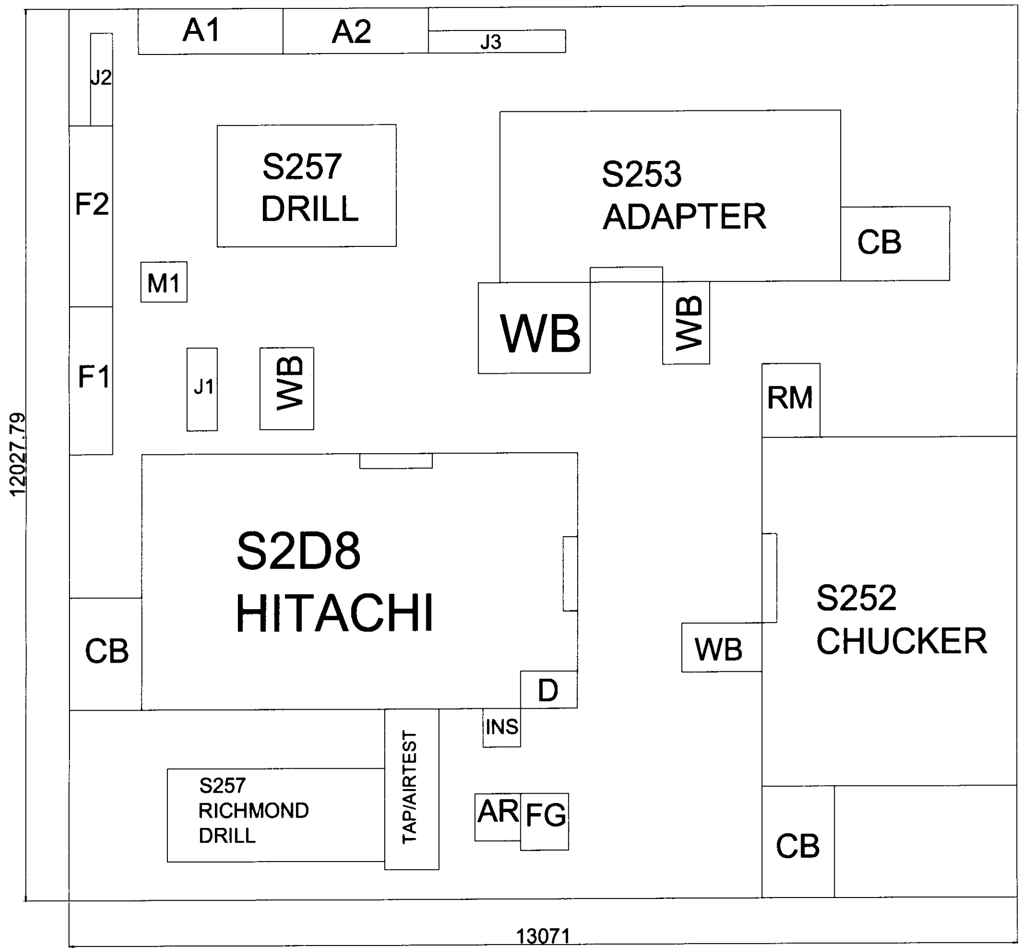


Figure C-3: Layout Concept 2

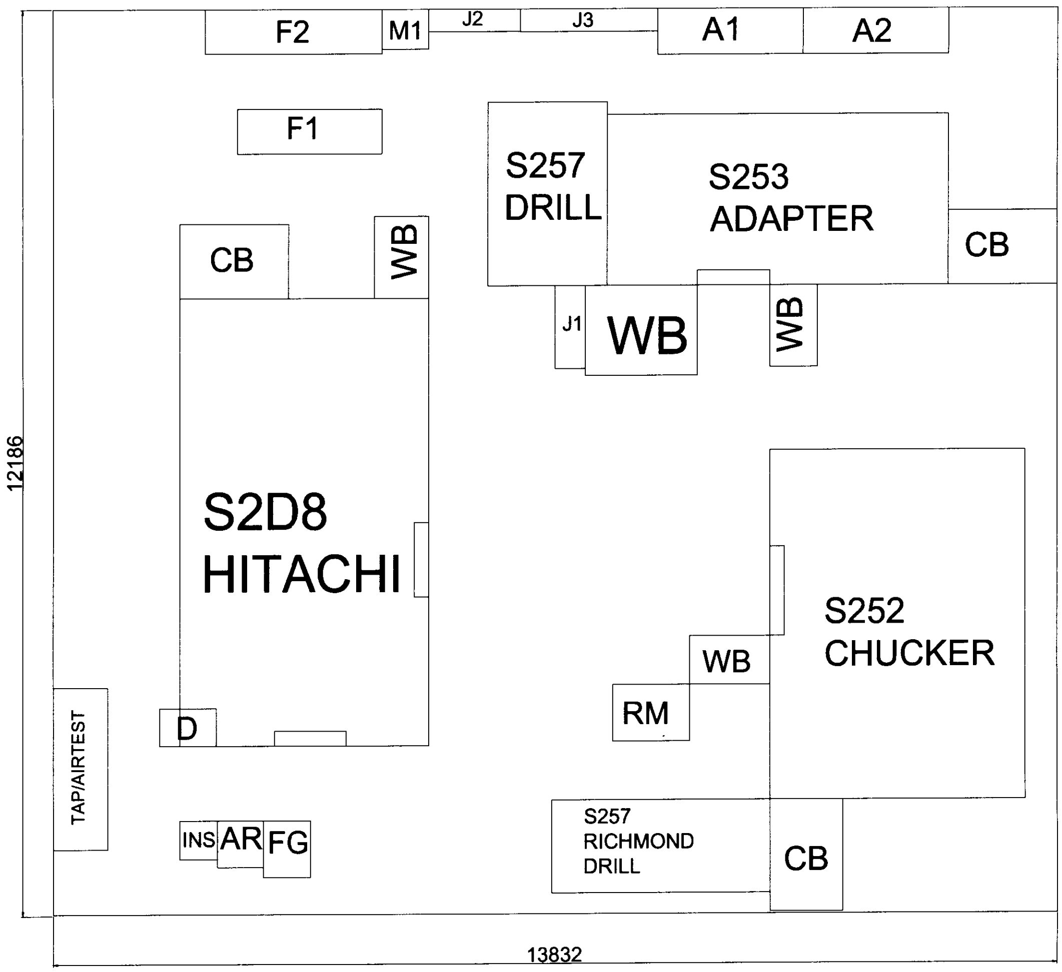


Figure C-4: Layout Concept 3

Appendix D: Inventory inaccuracy simulation spreadsheet

Safety Stock Calculations (Increase Reorder Point)

Mean demand/unit time	Standard Dev.	Q	SS	R	LT	Service factor (k)
10	3	40	15	45	3	1.65

Decision Variable

Forecasts

Lost sales(IRP)	% lost sales(IRP)
137.99	3.78

Day	Beg Inv Pos	Beg Inv	Order Rec'd	Units Rec'd	Demand	Stock disc.	Actual End Inv	Actual Lost Sales	Actual End Inv Pos.	Record end inv.	Record order placed	Rec week due
1	55	55		0	10	0.1	44.90	0.00	84.90	45.00	TRUE	5
2	84.90	44.90		0	10	0.1	34.79	0.00	74.79	34.99	TRUE	6
3	74.79	34.79		0	10	0.1	24.69	0.00	64.69	24.99	TRUE	7
4	64.69	24.69	FALSE	0	10	0.1	14.58	0.00	54.58	14.98	TRUE	8
5	54.58	14.58	TRUE	40	10	0.1	44.48	0.00	84.48	44.98	TRUE	9
6	84.48	44.48	TRUE	40	10	0.1	74.37	0.00	74.37	74.97	FALSE	0
7	74.37	74.37	TRUE	40	10	0.1	104.27	0.00	104.27	104.97	FALSE	0
8	104.27	104.27	TRUE	40	10	0.1	134.16	0.00	134.16	134.96	FALSE	0
9	134.16	134.16	TRUE	40	10	0.1	164.06	0.00	164.06	164.96	FALSE	0
10	164.06	164.06	FALSE	0	10	0.1	153.95	0.00	153.95	154.95	FALSE	0
11	153.95	153.95	FALSE	0	10	0.1	143.85	0.00	143.85	144.95	FALSE	0
12	143.85	143.85	FALSE	0	10	0.1	133.74	0.00	133.74	134.94	FALSE	0
13	133.74	133.74	FALSE	0	10	0.1	123.64	0.00	123.64	124.94	FALSE	0
14	123.64	123.64	FALSE	0	10	0.1	113.54	0.00	113.54	114.94	FALSE	0

Assumptions

Figure D-1: Increase in Reorder Point to compensate Inventory Inaccuracy

Constant Decrement in Inventory Record

Mean demand/unit time	Standard Dev.	Q	SS	R	LT	Service factor (k)	Average stock less/day
10	3	40	15	45	3	1.65	0.2

Decision variable

Forecasts

Lost sales(DR)	% lost sales(DR)
0.00	0.00

Day	Beg Inv Pos	Beg Inv	Order Rec'd	Units Rec'd	Demand	Stock disc.	Actual End Inv	Actual Lost Sales	Actual End Inv Pos.	Record end inv.	Record order placed	Rec week due
1	55.00	55.00		0	10.00	0.20	44.80	0.00	84.80	44.80	TRUE	5
2	84.80	44.80		0	10.00	0.20	34.59	0.00	74.59	34.59	TRUE	6
3	74.59	34.59		0	10.00	0.20	24.39	0.00	64.39	24.39	TRUE	7
4	64.39	24.39	FALSE	0	10.00	0.20	14.18	0.00	54.18	14.18	TRUE	8
5	54.18	14.18	TRUE	40	10.00	0.20	43.98	0.00	83.98	43.98	TRUE	9
6	83.98	43.98	TRUE	40	10.00	0.20	73.77	0.00	73.77	73.77	FALSE	0
7	73.77	73.77	TRUE	40	10.00	0.20	103.57	0.00	103.57	103.57	FALSE	0
8	103.57	103.57	TRUE	40	10.00	0.20	133.36	0.00	133.36	133.36	FALSE	0
9	133.36	133.36	TRUE	40	10.00	0.20	163.16	0.00	163.16	163.16	FALSE	0
10	163.16	163.16	FALSE	0	10.00	0.20	152.95	0.00	152.95	152.95	FALSE	0
11	152.95	152.95	FALSE	0	10.00	0.20	142.75	0.00	142.75	142.75	FALSE	0
12	142.75	142.75	FALSE	0	10.00	0.20	132.54	0.00	132.54	132.54	FALSE	0
13	132.54	132.54	FALSE	0	10.00	0.20	122.34	0.00	122.34	122.34	FALSE	0
14	122.34	122.34	FALSE	0	10.00	0.20	112.14	0.00	112.14	112.14	FALSE	0

Assumptions

Figure D-2: Constant Decrement of Inventory Record to compensate Inventory Inaccuracy

Appendix E: Safety Stock Calculation Spreadsheet

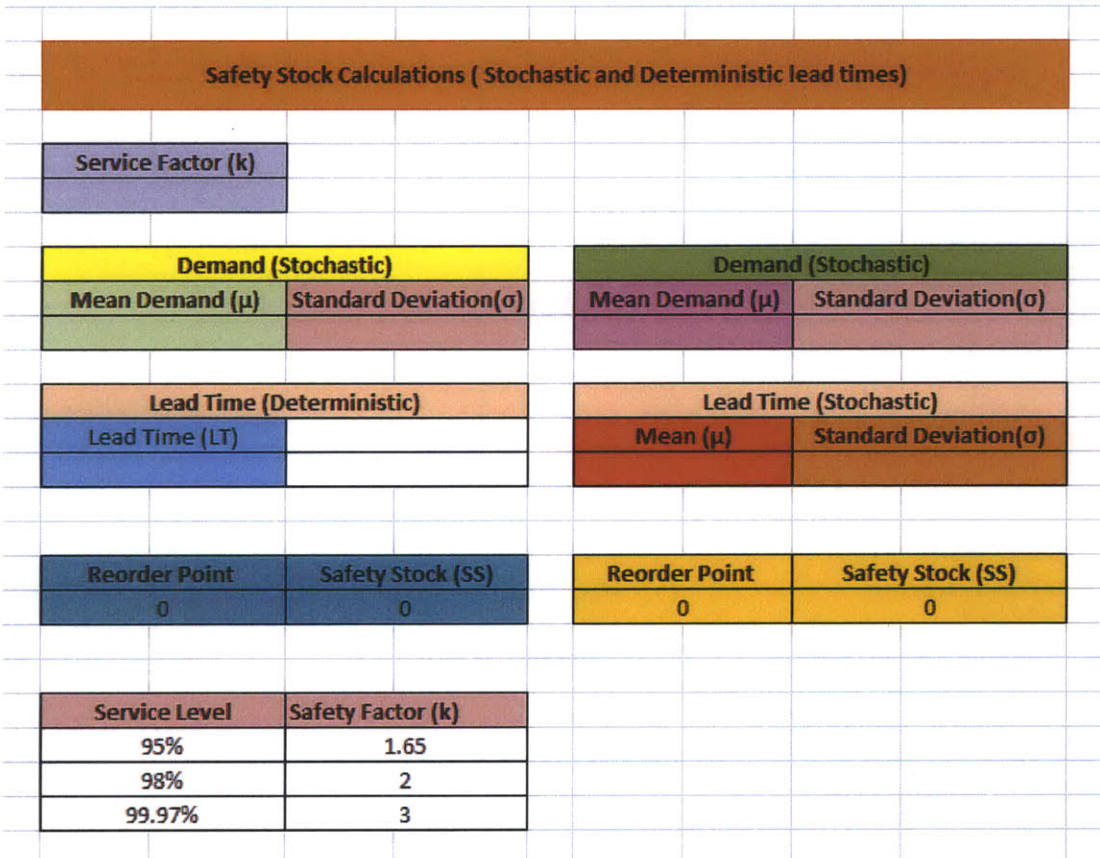


Figure E-1: Safety Stock calculations spreadsheet